REPORT NO. 2 (QUARTERLY)

PROJECTS NO. A-402-11, -12, AND -13

QUARTZ CRYSTAL STUDIES AND MEASUREMENTS

PHASE I. MOTIONAL PARAMETERS

By

HITOHIRO FUKUYO, ISSAC KOGA, J. E. RHODES,
YASUO TSUZUKI, AND S. N. WITT, JR.

PHASE II. EQUIVALENT ELECTRICAL PARAMETERS

By

S. N. WITT, JR. AND V. K. WOODCOX

PHASE III. AGING OF QUARTZ RESONATORS

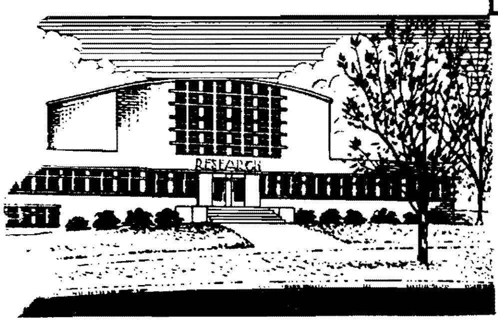
By

R. B. BELSER AND W. H. HICKLIN

CONTRACT NO. DA-36-039 SC-78905

1 JULY TO 30 SEPTEMBER 1959

PLACED BY THE U. S. ARMY
SIGNAL RESEARCH AND DEVELOPMENT LABORATORIES
FORT MONMOUTH, NEW JERSEY



Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia

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A stabilization system for the Marconi Signal Generator has been breadboarded and tested. The short-term stability of the generator was improved by a factor greater than 30. The longer-term improvement was by a factor of 10. The complete system, with schematic diagrams, is described in this report.

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Resonator aging ovens for operation of 100 mc units at 55°C and for cycling them through the range 0°C to 55°C have been completed; the oven for storage of resonators at 0°C has been about 75 percent completed.

Leak tests of approximately 400 additional, making a total of 569, industrially fabricated resonators of 16.25 mc/sec frequency have been completed by the use of the vacuum oil leak test. The number of leakers indicated by this test was 83 percent of the total. The percentage of leakers found for units stored at 85°C and 125°C was greater than for those stored at room temperature. This was in accordance to the greater frequency drifting observed previously for units stored at the higher temperatures.

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ENGINEERING EXPERIMENT STATION
of the Georgia Institute of Technology
Atlanta, Georgia

REPORT NO. 2 (QUARTERLY)

PROJECTS NO. A-402-11, -12, and -13

QUARTZ CRYSTAL STUDIES AND MEASUREMENTS

PHASE I. MOTIONAL PARAMETERS

By

HITOHIRO FUKUYO, ISSAC KOGA, J. E. RHODES,
YASUO TSUZUKI, AND S. N. WITT, JR.

PHASE II. EQUIVALENT ELECTRICAL PARAMETERS

By

S. N. WITT, JR. AND V. K. WOODCOX

PHASE III. AGING OF QUARTZ RESONATORS

By

R. B. BELSER AND W. H. HICKLIN

CONTRACT NO. DA-36-039 SC-78905

1 JULY TO 30 SEPTEMBER 1959

The object of this research is the enhancement
of the understanding of the behavior of quartz
crystals as frequency control and filter devices.

PLACED BY THE U. S. ARMY
SIGNAL RESEARCH AND DEVELOPMENT LABORATORIES
FORT MONMOUTH, NEW JERSEY

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(This report contains 76 pages.)

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LIST OF FIGURES (Continued)

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I. PURPOSE

The research being pursued under Contract No. DA-36-039 SC-78905 is a broad study of the behavior of quartz crystals as frequency control and filter elements. Three areas of specialization are being pursued:

Phase I. Motional Parameters

Phase II. Equivalent Electrical Parameters

Phase III. Aging of Quartz Resonators

Phase I is concerned with the study of the motional parameters of thickness shear modes of AT-cut quartz crystals. The purpose of Phase I is fourfold:

1. To measure as a function of the plate and electrode size the motional capacitance and shunt capacitance on quartz crystal disks of the AT-type in the frequency range 1 to 10 mc/sec;

2. To measure the motional capacitance of the inharmonic overtones as a function of the plate and electrode size, and to compare the functional dependence of the motional capacitance on the electrode size with the solution following from the strain distribution of the mode;

3. To measure the capacitance ratio and the shunt capacitance in its variation with the variation of the inharmonic overtones;

4. To investigate any other problems pertinent to motional parameters which may arise during the course of the studies as mutually agreed upon between the Contractor and the Contracting Officer's Technical Representative.

In Phase II, methods for measuring the equivalent electrical parameters of quartz crystal units will be investigated. The purpose of Phase II is fourfold:

1. To continue the study and investigation of methods and techniques for measuring the equivalent electrical parameters of VHF and UHF overtone quartz crystal units in the frequency range above 250 mc/sec, including

(a) determination of measurement errors,

(b) development of a means for directly measuring the power dissipation of the crystal units, and

(c) development of a procedure for specifying and measuring the significant parameters of the crystal unit at the overtone frequency of interest;

2. To utilize the information from Part 1, above, in the establishment of a standard crystal measurement system in the frequency range 100 to 500 mc/sec which will accomplish the following:

(a) measure the effective resistance of the crystal unit at the apparent series resonant frequency of the crystal unit with a target accuracy within one percent for resistance and 0.0001 percent for frequency,

(b) include a means of measuring directly the power dissipation of the crystal unit with an accuracy sufficient for 2(a), above, but not worse than 10 percent;

3. To utilize the information from Parts 1 and 2, above, in investigations of circuitry for the design and construction of an experimental model of a practical crystal test set for the frequency range 175 to 300 mc/sec. The desired characteristics of the test set follow:

(a) measurement of the effective resistance of the crystal unit in the range from 20 to 200 ohms, at the apparent series resonant frequency, within 5 percent.

(b) adjustment of the crystal power drive within 0.2 to 4 mw and direct determination of the driving power within 20 percent,

(c) frequency control within an absolute accuracy of 0.0002 percent at the apparent series resonant frequency of the crystal unit;

4. To investigate any other problems pertinent to crystal measurements in the VHF and UHF ranges which are mutually agreed upon by the Contractor and the Contracting Officer's Technical Representative.

Phase III will continue investigations into the causes of aging of quartz crystal units. The purpose of Phase III is fivefold:

1. To fabricate experimental crystal units of the CR-19/U type with highly polished crystal blanks in metal and glass holders;

2. To conduct investigations of frequency drifts induced by normal diffusion in multilayer electrodes produced in plating-to-frequency;

3. To conduct investigations on the diffusion of bonding materials and solder into monolayer gold and aluminum electrodes;

4. To investigate the feasibility of replacing the currently used solder sealing of metal containers with cold welding of metal parts;

5. To investigate any other problems pertinent to aging of crystal units which may arise during the course of the studies as mutually agreed upon between the Contractor and the Contracting Officer's Technical Representative.

II. ABSTRACT

Under Phase I, beveled circular crystal plates and triangular crystal plates were examined by Dr. Koga and Dr. Fukuyo. The spectra, polarization patterns, and other considerations indicated that the behavior of these crystals could not be fully explained until the simpler rectangular crystals have been further analyzed.

Dr. Fukuyo returned to Japan during this period. His equipment was shipped to the Tokyo Institute of Technology. Mr. Tsuzuki arrived from Japan with equipment from the Yokahama National University. All of Mr. Tsuzuki's equipment is now in operation.

The spectra studies of rectangular crystals have progressed rapidly. Mr. Tsuzuki has been able to trace all of the strong and many of the weak crystal responses through dimensional reductions averaging 8 microns per step. The spectral response resolution of his equipment is appreciably better than that of equipment previously used.

Polarization studies of the rectangular crystal have only recently begun and are not described in this report.

Under Phase II, additional improvements have been made in the component mount for the substitution measurement system. The resistance and frequency of 22 overtone responses of 9 crystals were measured with maximum errors of less than 4 percent and 0.0002 percent respectively.

A stabilization system for the Marconi Signal Generator has been bread-boarded and tested. The short-term stability of the generator was improved by a factor greater than 30. The longer-term improvement was by a factor of 10. The complete system, with schematic diagrams, is described in this report.

Under Phase III, the construction of the frequency measuring system for 100 mc/sec resonators has been completed. The system consists of an oscillator,

Cl meter TS-15 for driving the crystal, a VHF bridge and associated instruments for adjusting the crystal to resonance by means of a null detector, an amplifier and a frequency counter. Measurements rapidly made and accurate to within two parts in 10^8 appear to be consistently feasible, provided the frequency standard upon which measurements are based is of the necessary long-term stability.

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III. PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

No publications, lectures, or reports have resulted from work under this contract during this report period.

A general conference to define the technical program of all three phases of the project was held at USASRDL on September 3, 1959. The following Georgia Tech persons attended: Dr. A. L. Bennett, Dr. J. E. Rhodes, Jr., Dr. Issac Koga, Mr. Yasuo Tsuzuki, Mr. Samuel N. Witt, Jr., and Mr. R. B. Belser.

IV. FACTUAL DATA

A. Phase I. Motional Parameters

1. Introduction

This phase of the work, assigned the Project Number A-402-11 by the Engineering Experiment Station of the Georgia Institute of Technology, was initiated on 1 March 1959 and is a continuation of the work prior to that date on Contract No. DA-36-039 SC-78910, Project Number A-402-1. This report, for the period from 1 July 1959 to 30 September 1959, represents a continuation of the work described in the Interim Report for the preceding period of the current contract.

During August of this period, Dr. Fukuyo returned to Japan. His equipment was shipped to the Tokyo Institute of Technology. Prior to his departure, Dr. Koga and Mr. Tsuzuki arrived from Japan.

Some investigations of beveled circular crystals and of triangular crystals were conducted by Dr. Koga and Dr. Fukuyo during this period. Brief descriptions of these investigations are reported in Sections A.2. and A.3. of this chapter.

Mr. Tsuzuki's equipment from the Yokahama National University has been placed in operation. The spectral response studies were begun during the month of August. The polarization studies were started late in September.

2. The Beveled Circular Crystal Plates

Five beveled circular AT-cut crystal plates were supplied by the USASRDL for study of polarization patterns and spectra. Four of the plates were chipped at the edges to different extents. For the initial studies, the plate without chips (A) and the plate with the largest chip (B) were chosen. Dimensions of the two plates are shown in Figure 1. The orientation of the x- and z-axis were determined by means of polarized light.

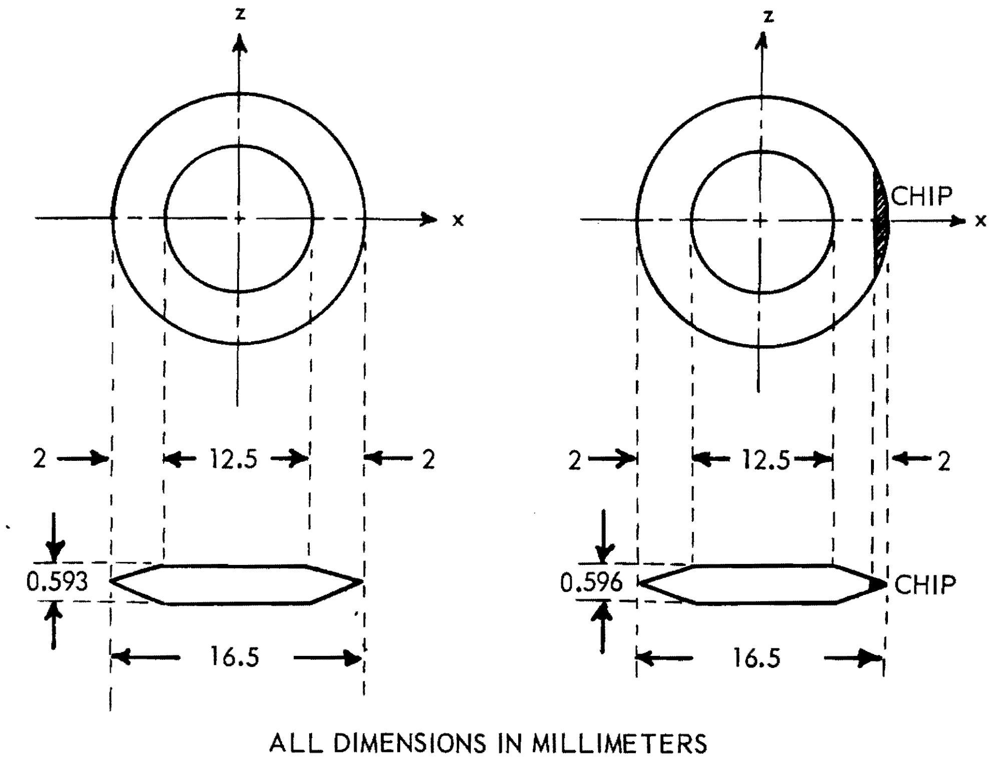
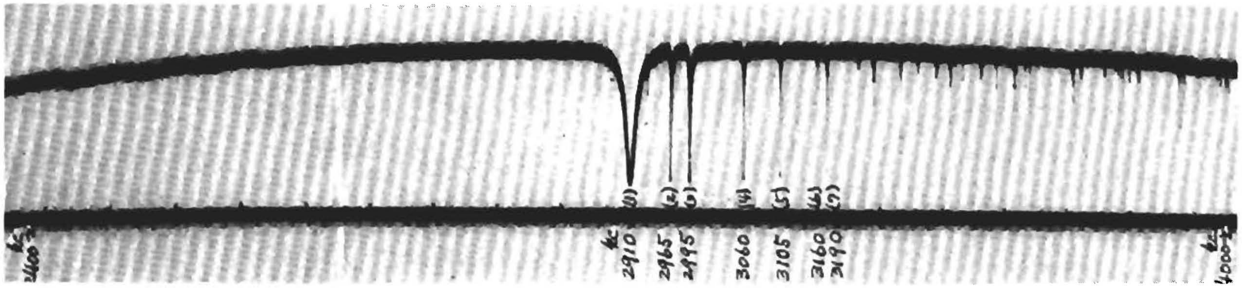


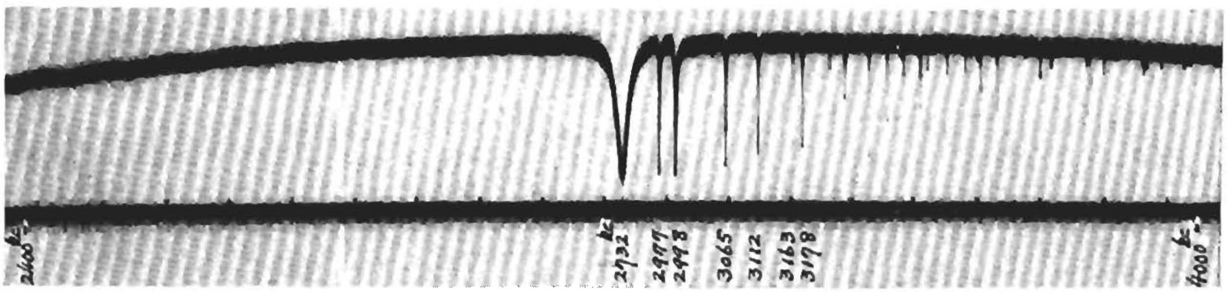
Figure 1. The Beveled Circular Test Crystal Plates.

Figure 2 shows the amplitude-versus-frequency spectra for the two plates. The frequencies of several of the stronger responses are marked on the oscillograms. The distinctive features of these beveled circular plates are that significant responses do not exist below the frequency of the principal thickness-shear vibration and that strong responses do not exist close to this frequency on the upper side.

For the polarization studies, the crystal plates were placed between two plane electrodes of diameter larger than the plates. Thus, the effects of polarization at the beveled surfaces could not be observed clearly. Figure 3 shows the polarization patterns for plate A along the x- and z-axis diameters for each of the 7 major responses shown in Figure 2.



A. BEVELED PLATE A



B. BEVELED PLATE B

Figure 2. Amplitude-Versus-Frequency Spectra of Two Beveled Circular Plates.

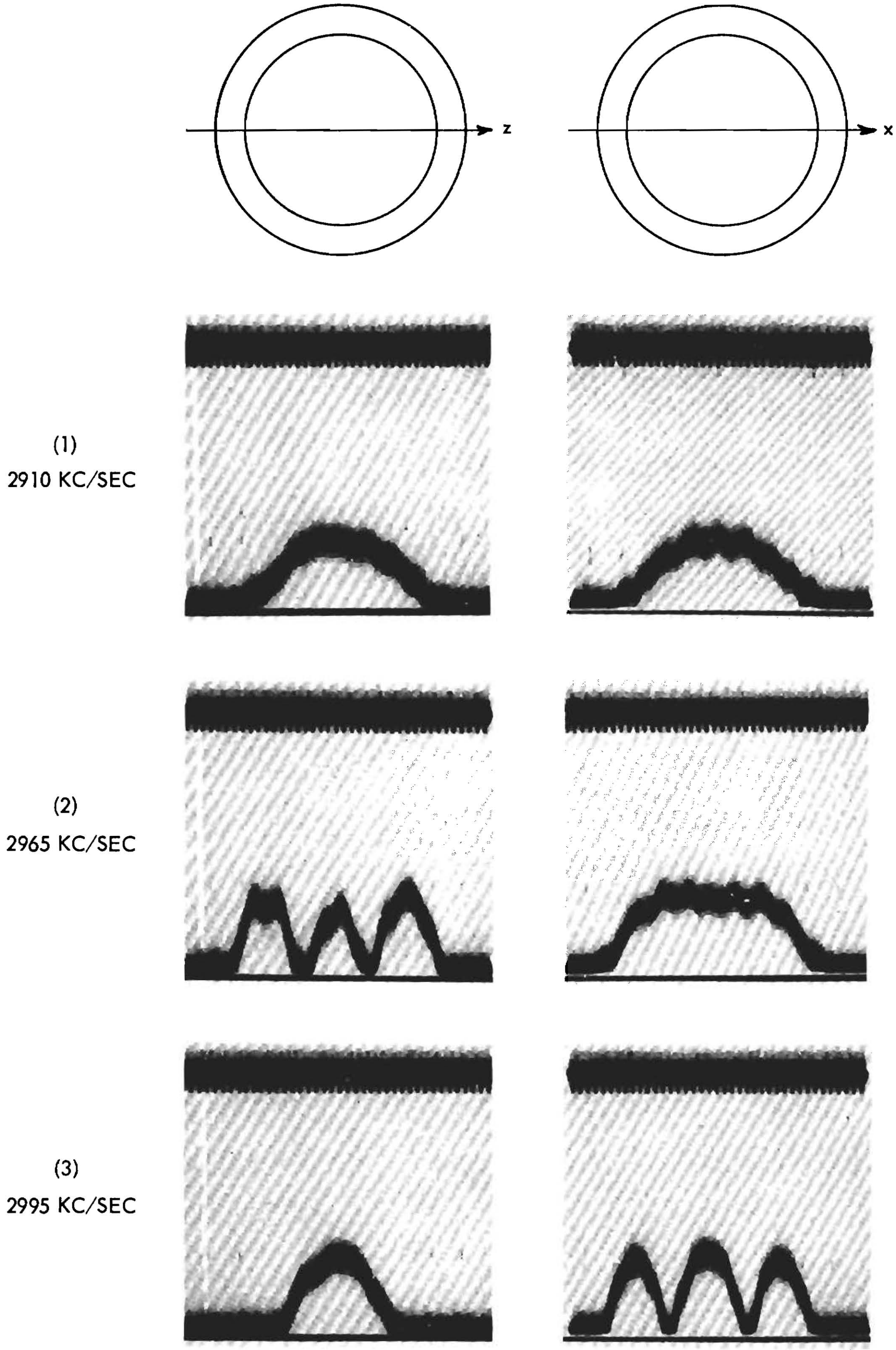
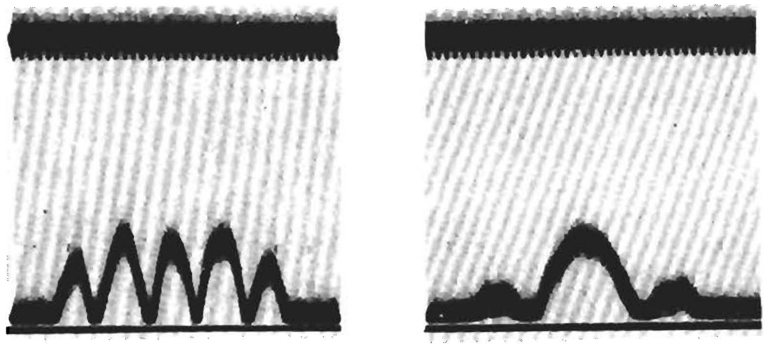
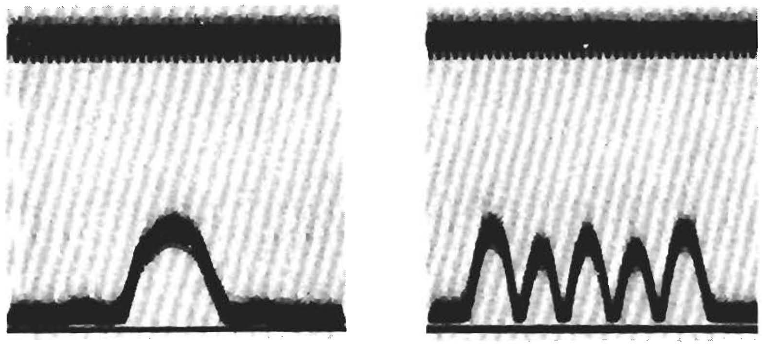


Figure 3. Polarization Patterns of Crystal A of Figure 2.

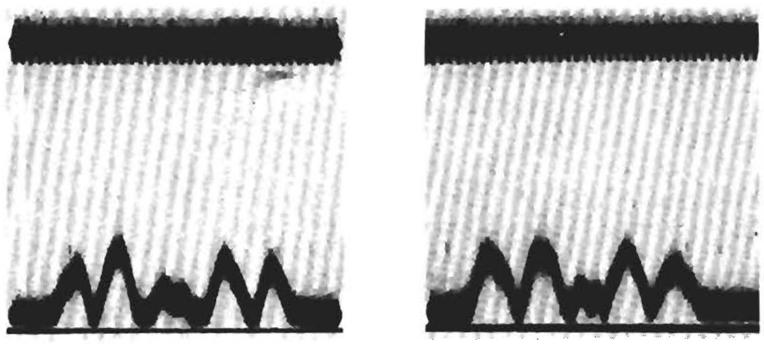
(4)
3060 KC/SEC



(5)
3105 KC/SEC



(6)
3160 KC/SEC



(7)
3190 KC/SEC

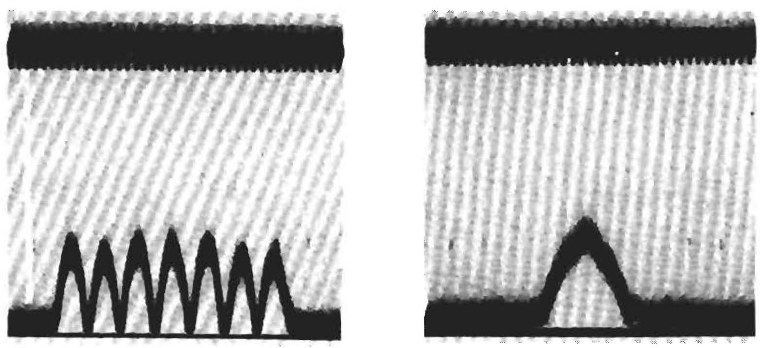


Figure 3 (Continued). Polarization Patterns of Crystal A of Figure 2.

The preliminary measurements indicate that available techniques can be used to clarify the behavior of the beveled circular crystal; however, this work will be deferred until the rectangular crystals are more fully understood.

3. The Triangular Crystal Plates

Brief investigations of the polarization and spectra of a typical 3 mc/sec triangular crystal plate were performed. The amplitude-frequency spectrum is shown in Figure 4. The polarization patterns corresponding to the stronger responses of Figure 4 are shown in Figure 5. The polarization patterns were obtained along both the x-axis and z-axis, through the center of the plate as indicated in Figure 5.

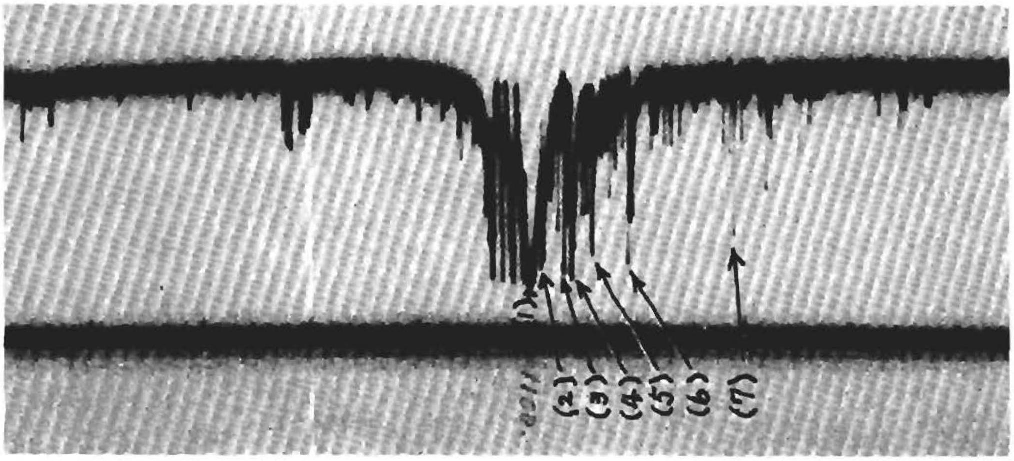


Figure 4. Amplitude-Versus Frequency Spectrum of a Triangular Crystal Plate.

The original five triangular crystal plates supplied by the USASRDL could not be examined since they were ground to a frequency of 10 mc/sec, whereas, the measurement equipment is designed to operate at 3 mc/sec. Accordingly, five crystal plates with the following specifications were procured:

Cut: AT at an angle of 35° 15' $\pm$ 2'. Orientation of the five plates to be within 2 minutes of each other.

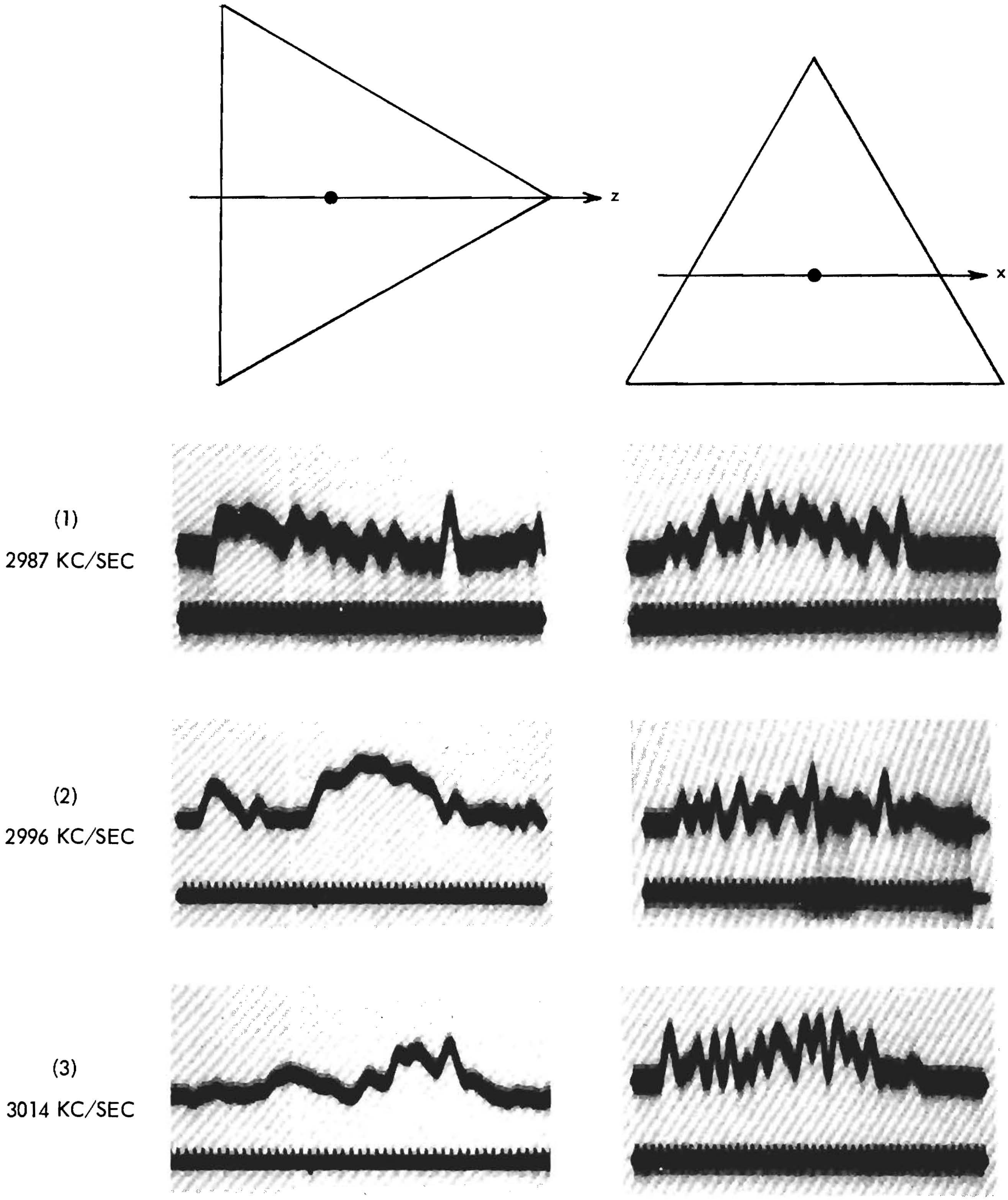


Figure 5. Polarization Patterns of the Crystal of Figure 4.

(4)
3018 KC/SEC

(5)
3033 KC/SEC

(6)
3060 KC/SEC

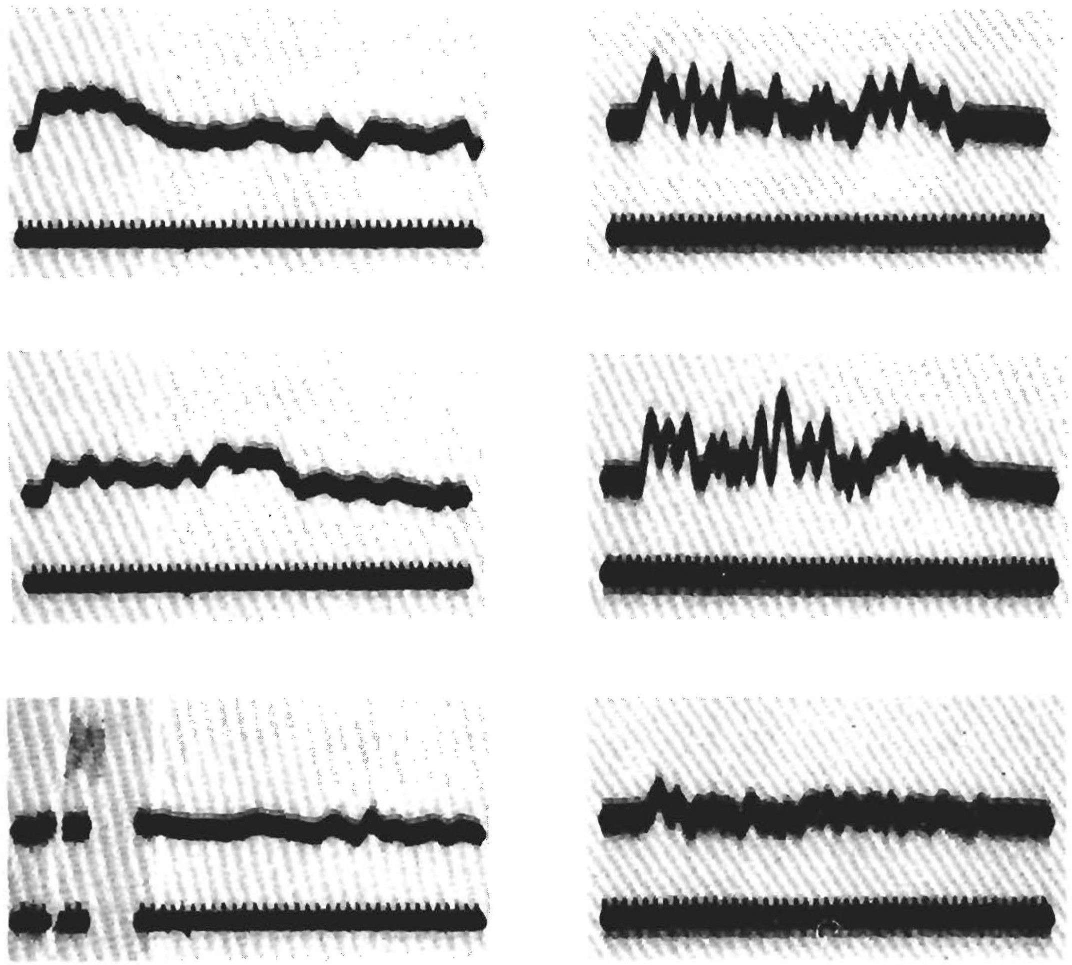


Figure 5 (Continued). Polarization Patterns of the Crystal of Figure 4.

Frequency:	3 mc/sec ± 10 kc/sec for the fundamental thickness-shear mode.
Shape:	Triangular, Equilateral.
Dimensions:	1.000" ± 0.010" each side; one side along the x-axis, ± 1°.
Operational Temperature:	25 ± 5°C.
Thickness:	As required by frequency.
Surface:	Milky white polish or, if necessary to obtain the required thickness, optical polish.

Four of the five crystals were chipped at one or more places on the edges when received. The plate without chips was chosen for the investigations.

The complexity of the vibrational patterns for the triangular plate is greater than that of the rectangular plate. The optimum design parameters for a specific crystal type can be determined only by changing the dimensions of the crystal and analyzing the various spectral responses and polarization patterns. For crystals in the shape of an equilateral triangle, the spectrum will be a function of the side-length and the specific orientation, where the specific orientation, ψ, is defined in Figure 6. Whether or not optimum selections of these quantities exist can be determined only by extensive studies.

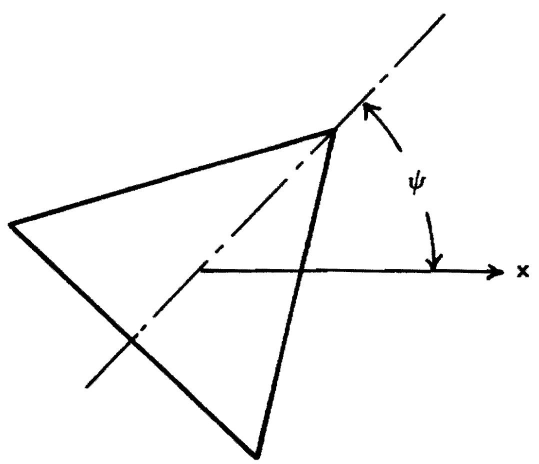


Figure 6. Definition of Specific Orientation, ψ.

4. Third Overtone Spectra of Rectangular Crystal Plates

a. Equipment for Mode Chart Preparation. During this report period, the equipment which was used by Dr. Fukuyo was returned to Japan. Mr. Tsuzuki brought similar equipment to this country from the Yokahama National University. Figure 7 is a block diagram of the equipment for recording the Spectra.

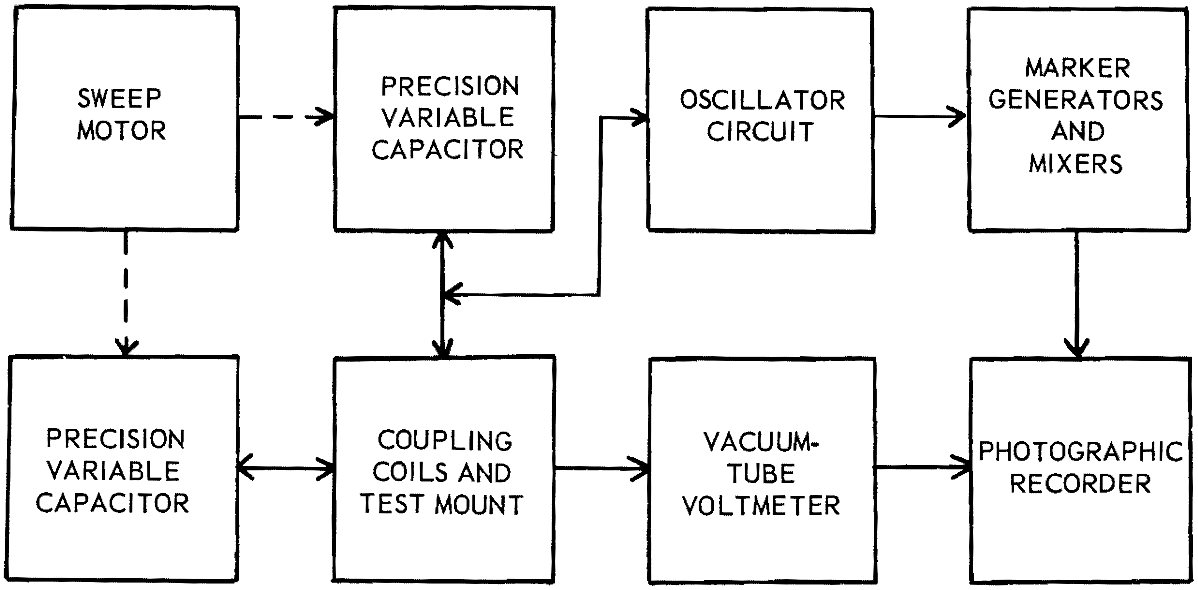


Figure 7. Block Diagram of the Equipment for Recording Spectra.

A schematic representation of the precision capacitors, coupling coils, and crystal test mount is shown in Figure 8. The capacitors, manufactured by

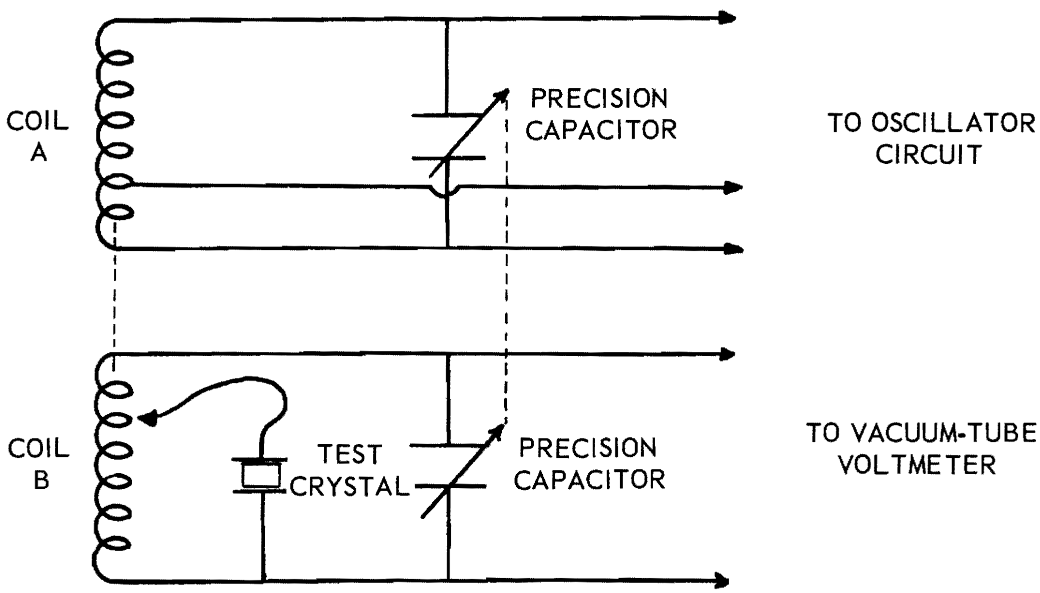


Figure 8. Elements of the System for Measurement of Spectra.

the Yokogawa Electric Works in Japan, have an approximately linear frequency variation with mechanical rotation. The coils A and B are constructed as nearly identical as possible so that proper tracking of the two resonant circuits can be obtained with the mechanically-coupled capacitors. The magnetic coupling between the coils is made as small as the sensitivity of the vacuum-tube voltmeter permits. A tap on coil A is provided for oscillator feedback and taps on coil B are provided for matching the impedance of the circuit to the response impedances of the test crystal.

Lack of perfect tracking of the two tuned circuits and lack of constant oscillator output cause the base-line of the resulting recordings to vary somewhat with frequency. These variations are of little concern however, since only the frequency and relative magnitudes of the responses are of importance in the present study.

The complete oscillator-detector circuit assembly is shown in Figure 9. Japanese vacuum tubes are presently used; however, American tubes with the same or corresponding numbers may be substituted.

The improved resolution of this equipment over previous recordings is made possible by the improved oscillator stability, the improved mechanical drive arrangement, and the direct injection of frequency markers. The minimum full-scale frequency deviation is $\pm$ 40 kc/sec. The deviation can be increased to approximately $\pm$ 400 kc/sec.

The photographic recorder is also manufactured by the Yokogawa Electric Works. Three vibrators are provided for three separate recording channels. The center vibrator, known as a type H vibrator in Japan, is used for the spectrum recordings and has a sensitivity of 10 mm/ma and a frequency response of 500 cps. The other vibrators are type A with a sensitivity of 0.5 mm/ma and a frequency response of 2 kc/sec.

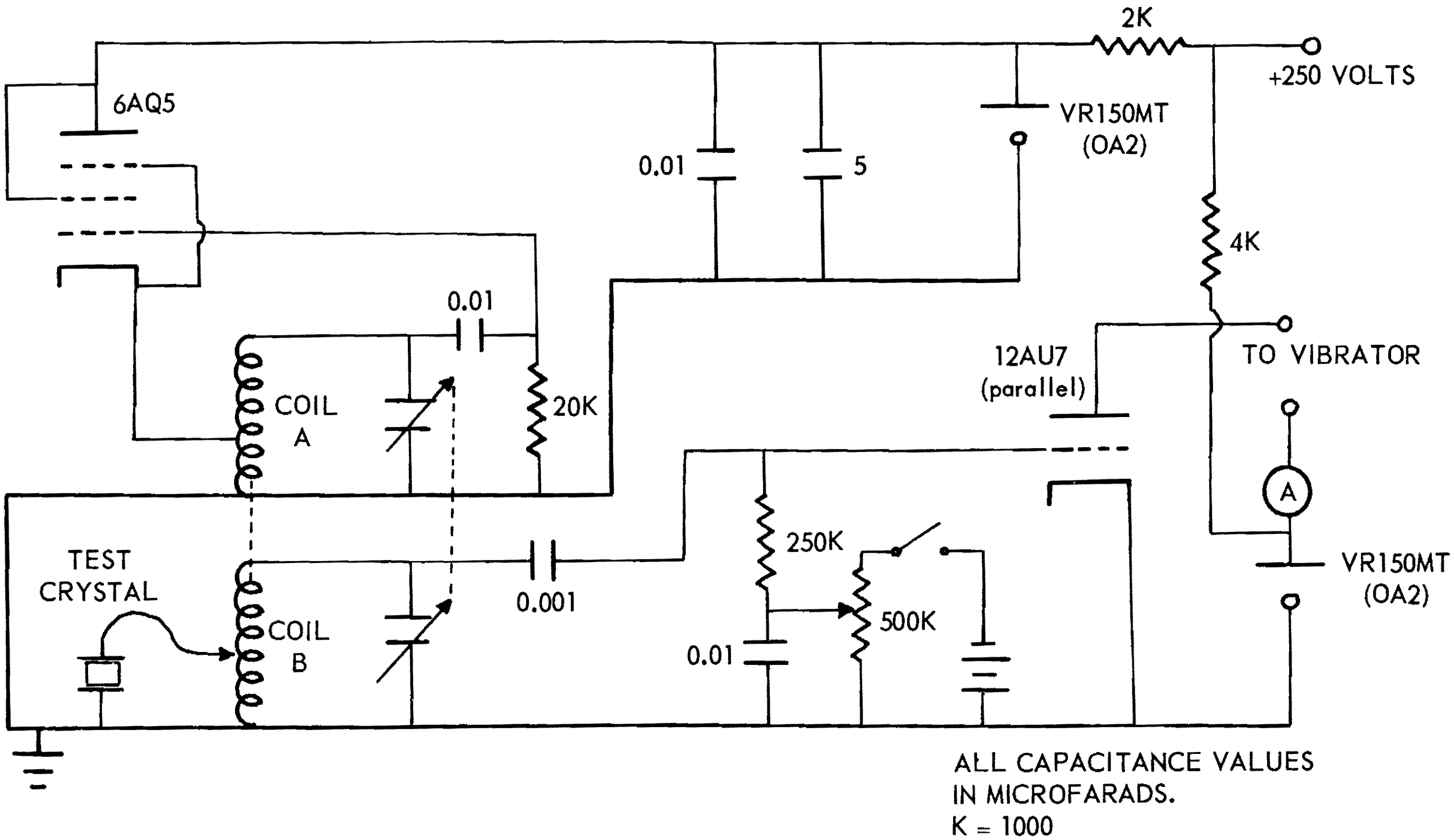


Figure 9. The Oscillator-Detector Circuit Diagram.

The frequency markers are provided by three crystal-controlled oscillators and a system of mixers. The oscillators operate at 10, 100, and 3000 kc/sec to provide strong frequency components with 10 kc/sec spacing in the region of 3000 kc/sec. These frequency components are mixed with the output of the crystal drive oscillator and the low-frequency heterodyne component is recorded by one of the Type A vibrators. The other type A vibrator is not used.

The photographic recorder and the test crystal drive-oscillator are driven by separate synchronous motors. Thus, the frequency variation on the recorded chart is approximately linear and interpolation may be used between the 10 kc/sec markers.

b. Preparation and Selection of Crystal Plates. For the initial spectral response studies, four parent quartz crystals, A, C, D, and E, were chosen. Each of these parent crystals was cut into four crystals with the following specifications.

Cut:	AT at an angle of $35^{\circ}\ 15' \pm 2'$.
Frequency:	Third overtone frequency approximately 3022 kc/sec.
Shape:	Rectangular, $x_o = 24.560$ mm $\pm$ 0.002 mm
	$y_o = 1.650$ mm $\pm$ 0.001 mm
	$z_o = 27.004$ mm $\pm$ 0.002 mm
Operational Temperature:	Room temperature, $25^{\circ}C \pm 5^{\circ}C$.
Surface:	Milky white polish or better.

Each of the crystals was numbered A-1, A-2, etc., the letter indicating the parent crystal.

The frequency spectra for all of the crystals were examined with the equipment which has been described. The two crystals showing the greatest similarity were D-1 and D-2. The high-resolution spectra of these crystals are shown in Figures 10 and 11. The spectra of the other crystals were similar to those of D-1 and D-2. For example, the spectral responses of a crystal from a different parent crystal is shown in Figure 12.

Crystals D-1 and D-2 were chosen for the spectra studies, D-1 for immediate use and D-2 for later use.

c. Mode Chart Preparation. In previous studies, only the relatively strong responses near the frequency of the thickness-shear vibration have been analyzed for AT-cut crystals. The improved resoltuion of the current equipment has made possible the studies of many of the weak responses also. The frequencies of these weak responses can be readily determined from spectra such as shown in Figure 10. Lower-resolution spectra such as shown in Figure 13 for crystal D-1 are useful in following the stronger responses.

As has been reported previously, the crystal mode charts are prepared by reducing an appropriate dimension of the crystal plate in steps sufficiently small to permit tracing of the individual responses. At first, the x_o dimension of crystal D-1 was reduced in steps of 20 microns. This reduction was more than adequate for tracing all of the strong responses; however, it was much too large to permit reliable tracing of the smaller responses. The dimensional reduction was thus changed to less than 10 microns per step. To date, approximately 45 dimensional reductions have been made with an average step of about 8 microns. Figure 14 shows the mode chart plotted for the weaker responses of crystal D-1. Some of the minor responses cannot be traced through the dimensional reductions. In this figure, the minor divisions in the x_o direction represent 10 microns.

Figure 15 shows the stronger crystal responses as plotted from low-resolution spectra oscillograms such as Figure 13. This mode chart is plotted for dimensional reductions of approximately 50 microns per step. Such reductions are more than adequate for proper tracing of strong responses.

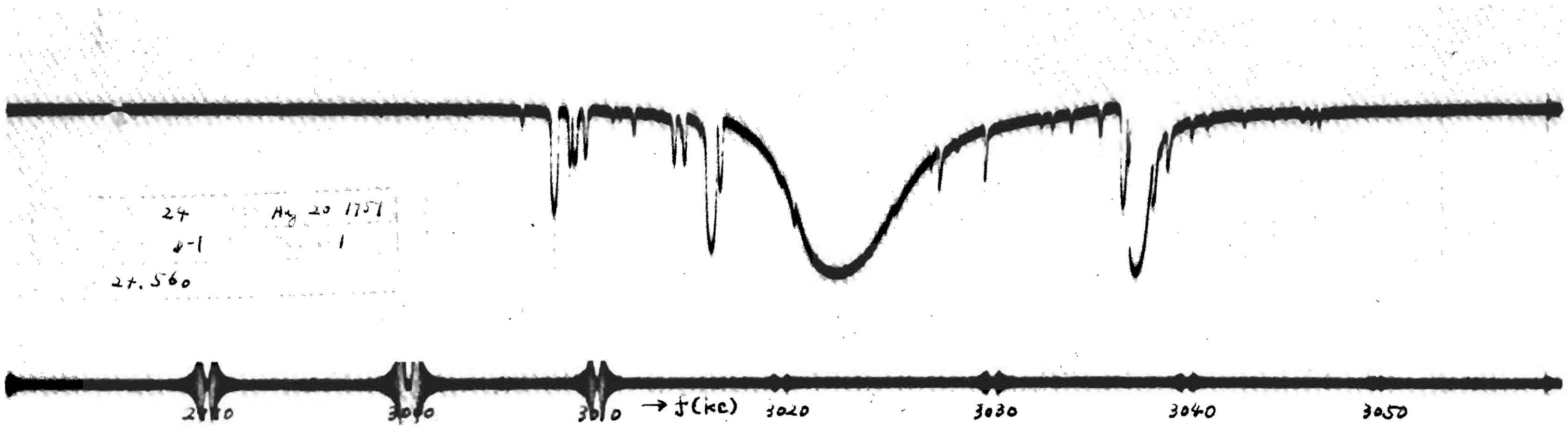


Figure 10. High-Resolution Spectrum of Crystal D-1.

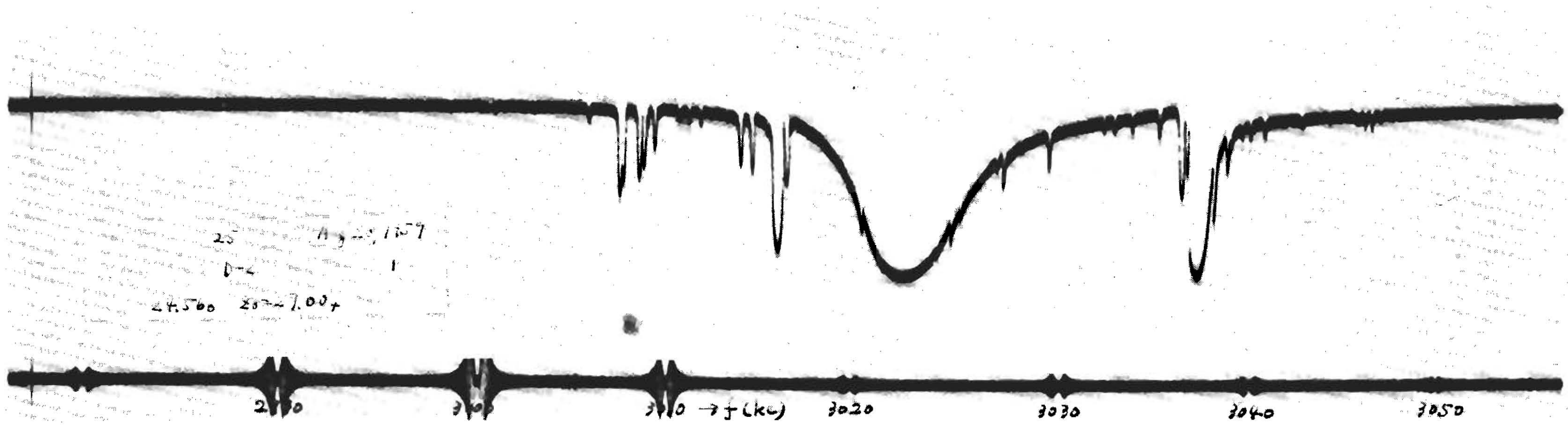


Figure 11. High-Resolution Spectrum of Crystal D-2.

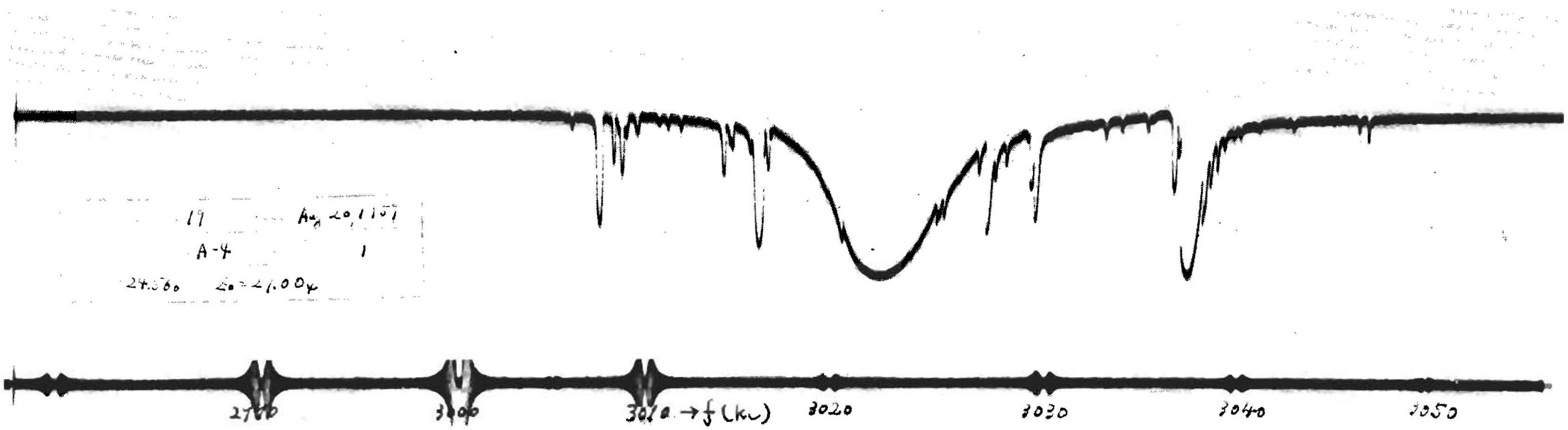


Figure 12. High-Resolution Spectrum of Crystal A-4.

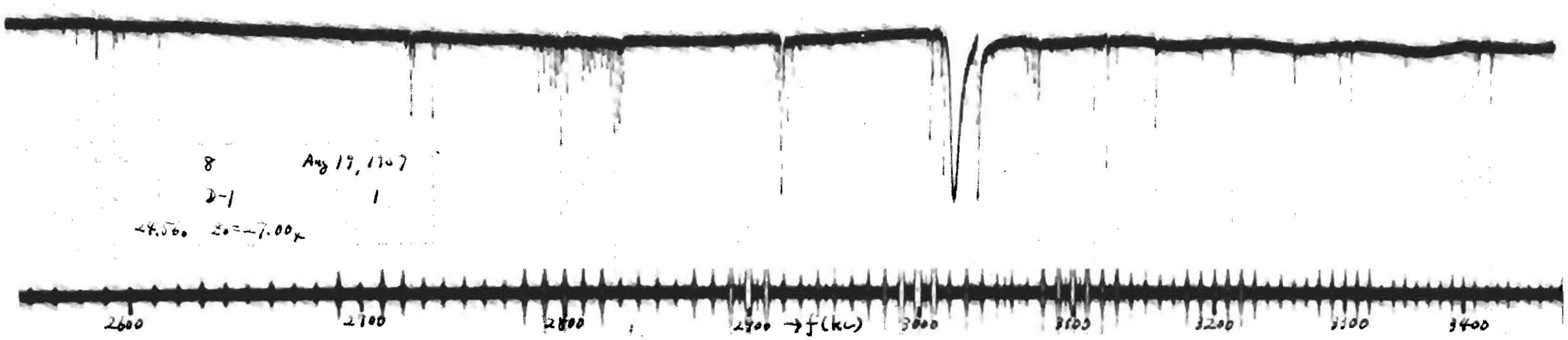


Figure 13. Low-Resolution Spectrum of Crystal D-1.

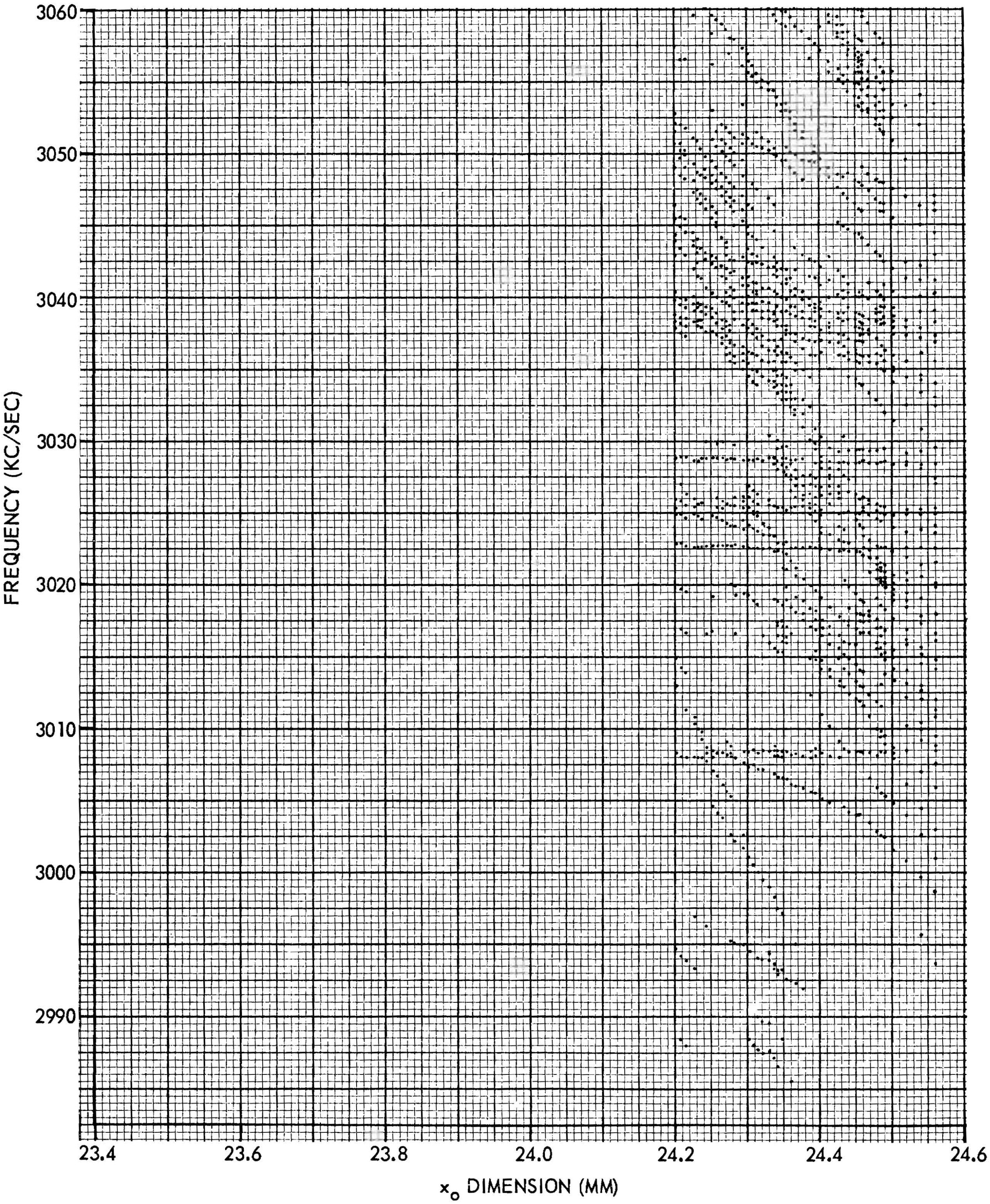


Figure 14. Mode Chart of Weaker Responses of Crystal D-1.

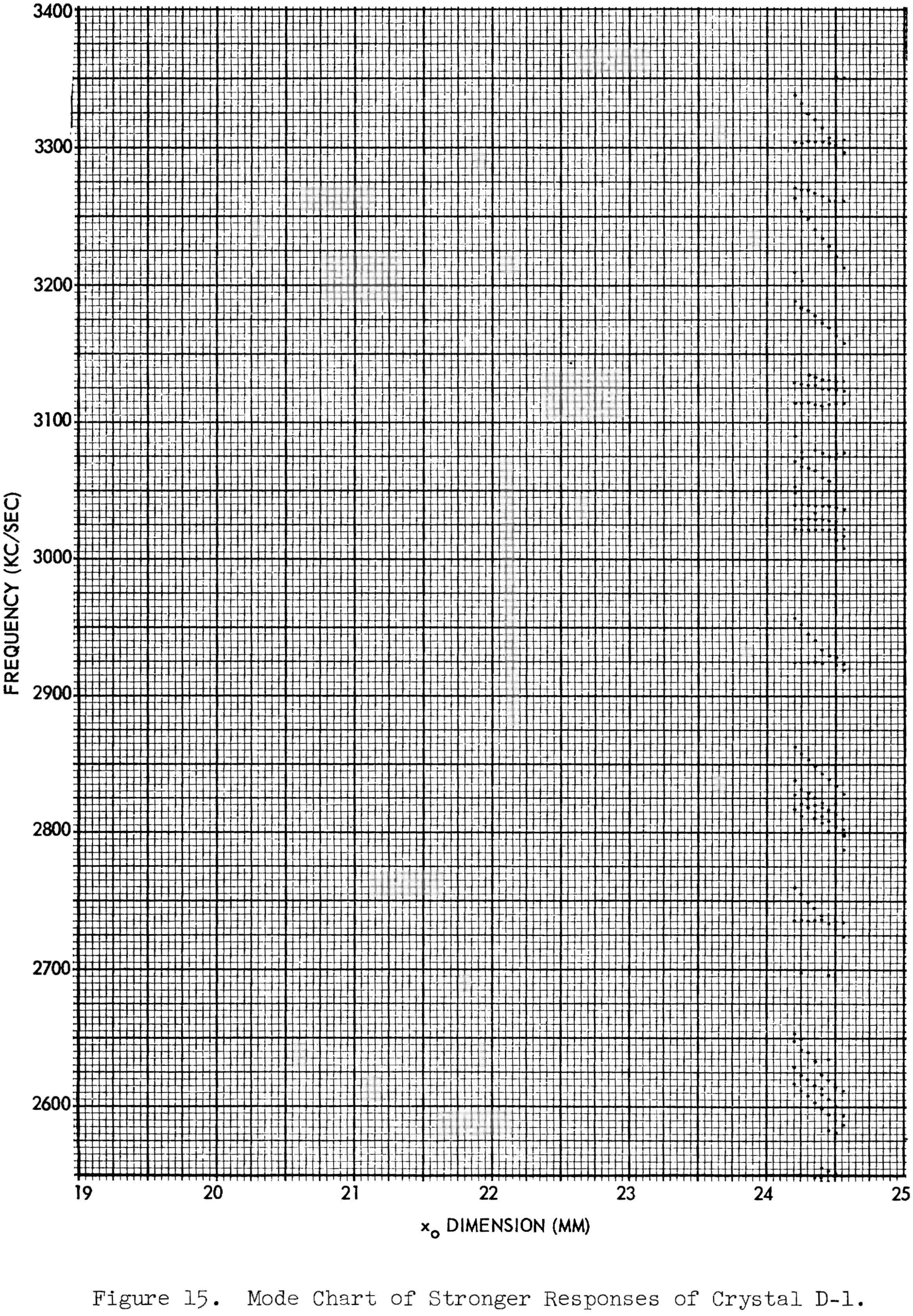


Figure 15. Mode Chart of Stronger Responses of Crystal D-1.

The completion of Figures 14 and 15 for crystal D-1 will require about six more months. Equipment for making polarization studies is now in operation and will aid greatly in identifying and tracing the various modes.

5. Polarization Studies

Equipment for making polarization studies has recently been assembled and is now in operation. This equipment consists of the necessary mechanical drive equipment, the source generator, and the detector-recorder equipment shown in Figure 16. The equipment presently in use is similar to that used by Dr. Fukuyo.

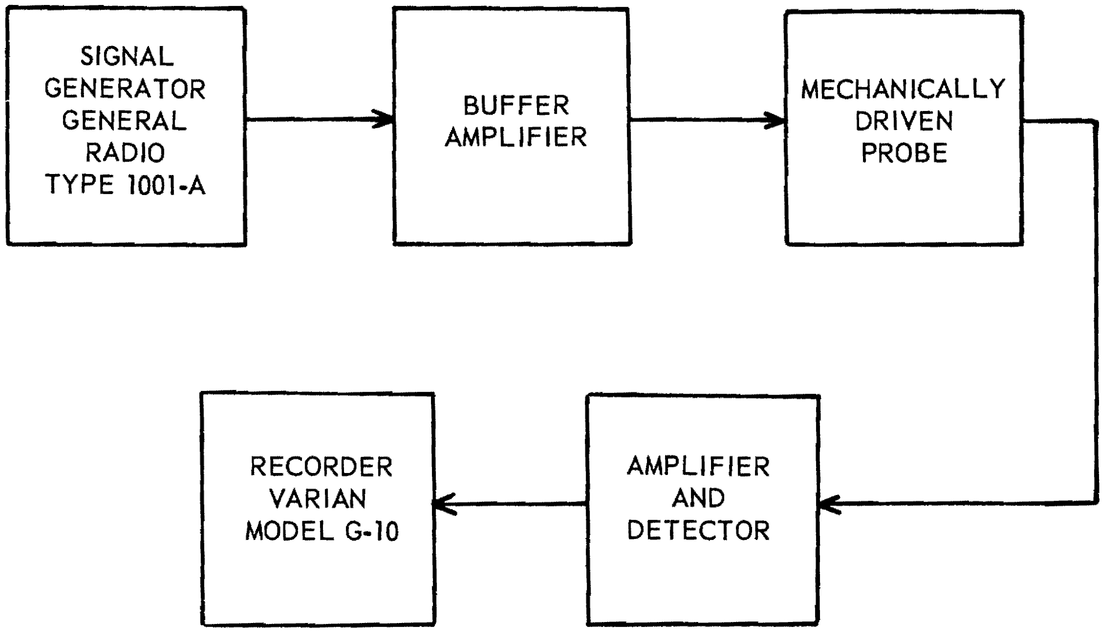


Figure 16. Block Diagram of Equipment for Polarization Studies.

In the previous equipment, however, a photographic oscillograph was used as the recorder. With this instrument immediate observation of the polarization patterns could not be made. In the current equipment a Varian Model G-10 pen recorder has been substituted.

Because of the much lower frequency response of the Varian recorder (one second for full-scale travel), the dimensional sweep speed across the crystal had to be reduced to approximately 10 mm/min. The lower speed required improved frequency stability of the signal source generator. Further improvements in stability were necessitated by the contemplated measurement of weak responses. The General Radio Type 1001-A Signal Generator, presently in use, has only marginal stability for this purpose. In addition, correlation of the polarization patterns with the frequency spectrum is very difficult since provision is not made for determining the frequency accurately. The polarization measurement equipment must be further refined before maximum usefulness can be realized.

B. Phase II. Equivalent Electrical Parameters

1. Introduction

This phase of the work, assigned the Project Number A-402-12 by the Engineering Experiment Station of the Georgia Institute of Technology, was initiated on 1 March 1959 and is a continuation of the work prior to that date on Contract No. DA-36-039 SC-78910, Project Number A-402-2. This report, for the period from 1 July 1959 to 30 September 1959, represents a continuation of the work described in the Interim Report for the preceding period of the current contract.

A substitution measurement system for determining the parameters of high-frequency quartz crystals was described in the Interim Report. The system consists of a component mount into which the crystal or substitution resistor is plugged, a signal source, and a suitable voltmeter. Two models of the component mount were previously described. Data were presented to compare the measurements from the substitution system with those from the Crystal Measurements Standard System.

2. The Substitution Measurement System

Further work to improve the accuracy of the substitution measurement system has continued. A study of the possible causes of error has indicated that the major source of conductance measurement error was the placement of the crystal with respect to the center conductor of the component mount. The reference plane of the Crystal Measurements Standard System is perpendicular to the pins and tangent to the base of the crystal unit. For best data agreement, an identical mount should be used for the substitution system; however, the nature of the substitution system prohibits this arrangement.

With either the Measurements Standard System or the substitution measurement system, the physical spacing between the crystal base and the measurement plane greatly affects the resulting data. The mount of the Measurements Standard System has been standardized so that the measurement plane is in contact with the crystal base. With the first and second prototype mounts for the substitution system the spacings between the measurement plane and crystal base were approximately 0.2 cm and 0.1 cm, respectively.

The spacing between the crystal base and the measurement plane for the second mount could not be appreciably reduced without shorting the center conductor of the mount to the crystal can. However, because of the compound curvature of the center conductor of the first mount, the spacing between the point of contact with the crystal pin and the base of the crystal could be made negligible. Also, the physical construction of the first mount more closely resembled that of the Measurements Standard System mount.

The first prototype mount was rebuilt by recessing the grounded pin connector so that the crystal base would be in contact with the measurement plane. The second connection to the center conductor was provided by drilling two intersecting holes as shown in Figure 17. A metal plunger and spring were inserted into the hole along the conductor axis as shown. The other hole was made smaller than the hole along the axis and only slightly larger than the crystal pin so that the spring pressure could provide good electrical and mechanical connections. The holes, because of their small diameters, should not appreciably affect the impedance of the transmission line.

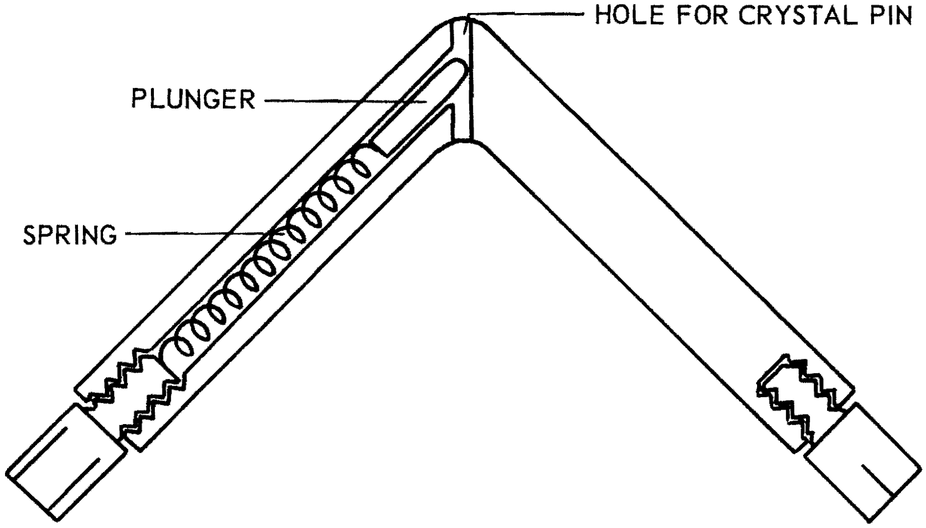


Figure 17. Cross-Section View of the Center Conductor of the Substitution Mount.

The position of the crystal in the mounts causes only relatively small errors in the measurement of the crystal resonant frequency and thus cannot account for the frequency errors of Table II of the Interim Report. Remeasurements of both the substitution data and the Measurements Standard data indicated that the major portions of the errors were due to crystal parameter changes. The Measurements Standard data had been obtained several months previously. During the intervening time, the crystals had aged and some had even developed small vacuum leaks. The room temperature during the Standard runs was 70°F or less compared to about 95°F during the substitution measurements. These factors resulted in appreciable changes in the resonant frequencies of the crystals. In some cases, the changes were compensating and resulted in accuracies better than the normal capabilities of the equipment. To obtain a valid comparison, the crystals must be measured by both systems at approximately the same time and under as nearly identical conditions as possible.

The Measurements Standard data was rerun by setting up the Admittance Meter for half-wavelength line measurements at each crystal overtone response to eliminate the digital computer calculations. The maximum conductances were determined by varying the signal generator frequency, obtaining a null, observing the conductance, and then changing the frequency by a small increment. This process was repeated until the maximum conductance was found. The conductance and frequency were then recorded. Corresponding measurements were then obtained with the substitution system. The approximate time required for the Measurements Standard data was 20 to 30 minutes per response compared to about 3 minutes per response for the substitution system.

Table I shows a comparative summary of the measurements by the two methods. The maximum error in the substitution resistance measurements is less than 4 percent and the maximum error in the substitution frequency measurements is less than 0.0002 percent with respect to the Measurements Standard System data.

TABLE I

MINIMUM RESISTANCE AND CORRESPONDING FREQUENCY MEASUREMENTS OBTAINED WITH THE SUBSTITUTION MEASUREMENT SYSTEM AND WITH THE CRYSTAL MEASUREMENTS STANDARD SYSTEM

Crystal No.	Substitution Measurement System		Crystal Measurements Standard		Res. Error	Frequency Error
	Frequency (Mc/Sec)	Resistance (Ohms)	Frequency (Mc/Sec)	Resistance (Ohms)	(%)	(%)
5	217.0975	127	217.0976	125	+1.6	-0.00005
5	250.4960	130	250.4959	129	0.8	0.00004
5	283.8947	106	283.8949	105	1.0	-0.00007
6	217.1018	116	217.1015	115	0.9	0.00014
6	250.5010	110	250.5008	109	0.9	0.00008
6	283.9009	85	283.9007	85	0.0	0.00007

(Continued)

TABLE I (Continued)

Crystal No.	Substitution Measurement System Frequency (Mc/Sec)	Substitution Measurement System Resistance (Ohms)	Crystal Measurements Standard Frequency (Mc/Sec)	Crystal Measurements Standard Resistance (Ohms)	Res. Error (%)	Frequency Error (%)
MA-23	178.1870	154	178.1872	149	3.4	0.00011
MA-23	210.5827	187	210.5827	182	2.8	0.00000
MA-23	242.9769	170	242.9766	167	1.8	0.00012
MA-24	178.1822	149	178.1825	145	2.8	-0.00017
MA-24	210.5771	177	210.5772	172	2.9	-0.00005
MA-24	242.9690	164	242.9690	162	1.2	0.00000
MA-25	178.1970	150	178.1970	153	-1.9	0.00000
MA-25	210.5948	153	210.5948	155	-1.3	0.00000
MA-25	242.9902	143	242.9905	143	0.0	-0.00012
MA-26	178.1886	122	178.1887	119	2.5	-0.00006
MA-26	210.5846	139	210.5843	141	-1.4	0.00015
MA-35	178.1818	155	178.1818	157	-1.3	0.00000
MA-35	210.5752	182	210.5754	185	-1.6	-0.00010
MA-37	178.1868	140	178.1867	139	0.7	0.00006
MA-37	210.5807	172	210.5807	175	-1.7	0.00000
FA-67	269.9675	72	269.9670	72	0.0	0.00018

Further tests of the substitution measurement system were not conducted at this time because of the poor stability of the Marconi Signal Generator.

3. Stabilization of the Marconi Signal Generator

Tests conducted with the Crystal Measurements Standard System during previous contracts indicated that the frequency stability of the Marconi Signal Generator Type 1066/1 was only marginally adequate for the purpose when the instrument was first received from the factory. The stability of the instrument became poorer with age. Also, higher Q crystals became available for laboratory tests. Since the Signal Generator stability was no longer adequate, the instrument was returned to the factory for repair. Some, although not sufficient, improvement in the frequency stability resulted.

A method has been devised to improve the frequency stability of the Marconi Signal Generator or other similar instruments. The method is block-diagrammed in Figure 18. The output of the Signal Generator is injected into

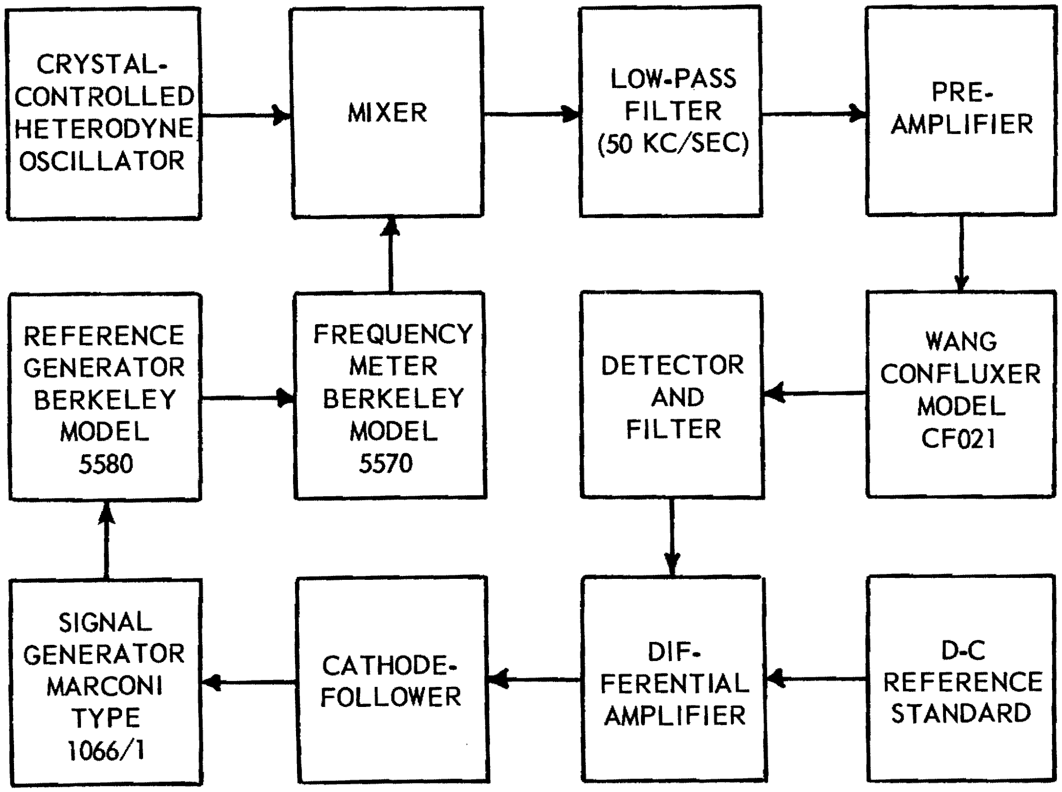


Figure 18. Block Diagram of the Marconi Signal Generator Frequency-Stabilization System.

the Berkeley Reference Generator (with the proper plug-in unit) where it is converted to a frequency between 2 and 32 mc/sec. This latter frequency is injected into the Frequency Meter for conversion to a frequency between 100 and 1100 kc/sec. This lower frequency is displayed directly on the decimal counter units of the Frequency Meter and is also supplied to an external mixer. The other input to the mixer is from a crystal-controlled heterodyne oscillator unit, the output of which may be switched in frequency from 25 to 1100 kc/sec in steps of 25 kc/sec. The frequency of the heterodyne oscillator is adjusted below that from the Frequency Meter so that the mixer output is between 25 and 50 kc/sec. A low-pass filter is used to attenuate the mixer input frequencies and unwanted modulation products. The output from the filter is amplified and shaped for injection into a Wang Laboratories Confluxer Model CF021. The output of the Confluxer is a constant area pulse for each input cycle. Since this output is magnetically coupled, a detector is necessary to produce a d-c voltage which is proportional to the input frequency. An R-C filter is also used to attenuate the pulsations of the d-c voltage. This filtered d-c voltage is compared with an adjustable standard d-c voltage supplied by a battery and a Helipot. A differential-amplifier is used as the comparator to provide additional d-c gain. The output from the differential-amplifier is shifted in d-c voltage level and supplied to a cathode-follower the output of which is coupled to the frequency-modulation input of the Marconi Signal Generator. The frequency-modulation input of the Signal Generator has the necessary direct-coupled feature.

A schematic diagram of the Crystal-Controlled Heterodyne Oscillator is shown in Figure 19. The outputs of two electron-coupled Pierce oscillators are mixed to produce difference output frequencies between 25 and 1100 kc/sec. A total of 44 crystals with 25 kc/sec frequency spacing from 6000 to 7075 kc/sec are switched, one at a time, in one of the oscillators. Two switches are used, one to provide frequency steps of 100 kc/sec and the other to provide the 25 kc/sec steps. The second oscillator is presently crystal controlled at 5975 kc/sec but will eventually be made switchable from 5975 to 5995 kc/sec in steps of 5 kc/sec. The heterodyne oscillator could thus be used with the Frequency Meter system and a 5 or 10 kc/sec analog converter to record the frequency variations of oscillators over the entire frequency spectrum up to 500 mc/sec. A crystal diode mixer, amplifier, filter, and various cathode-followers provide the necessary output voltage from the heterodyne oscillator.

The Mixer portion of the block diagram of Figure 18 is diagrammed in Figure 20. A vacuum dual diode is used as a full-wave rectifier which provides

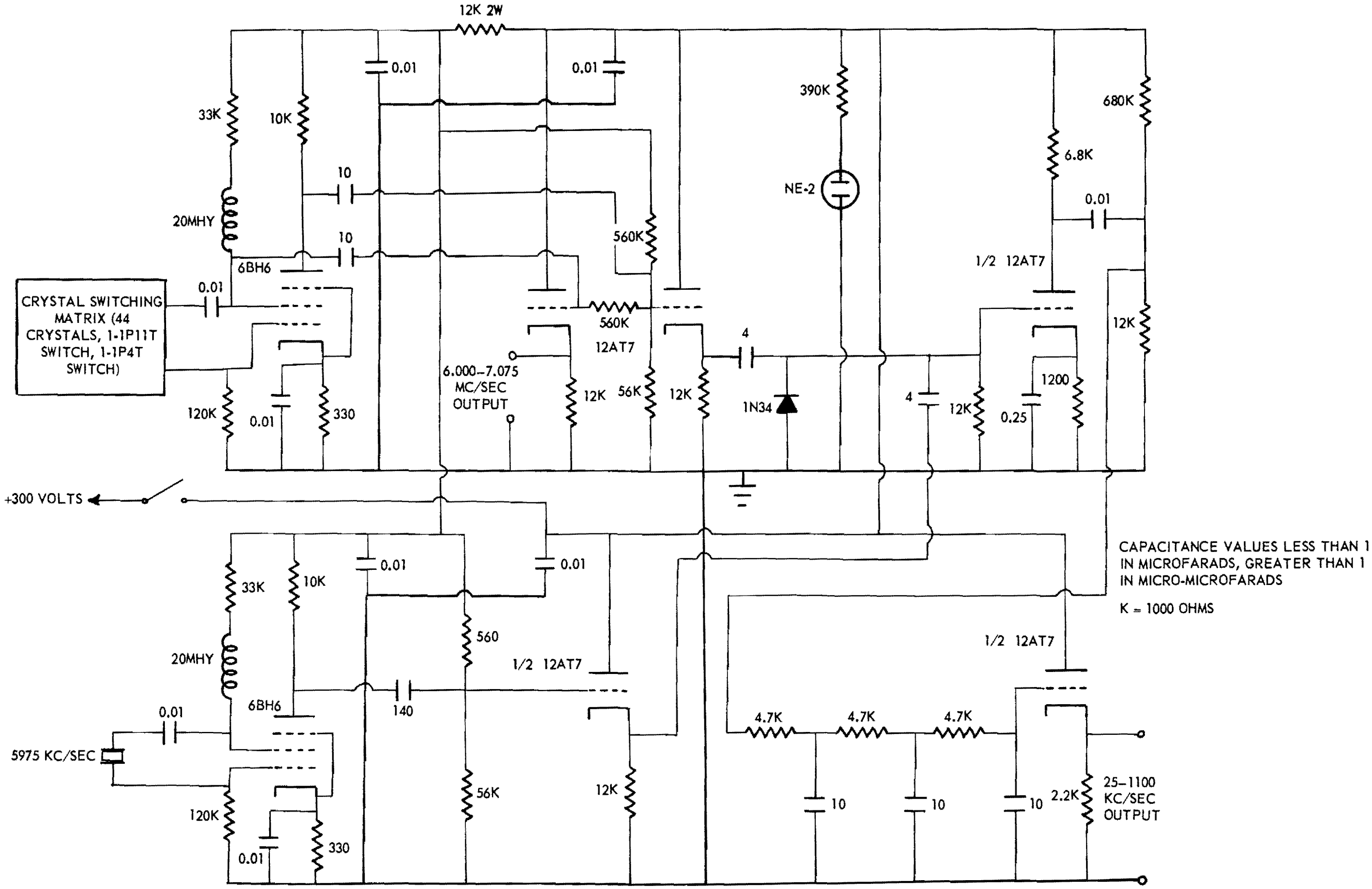


Figure 19. Circuit Diagram of Crystal Controlled Heterodyne Oscillator.

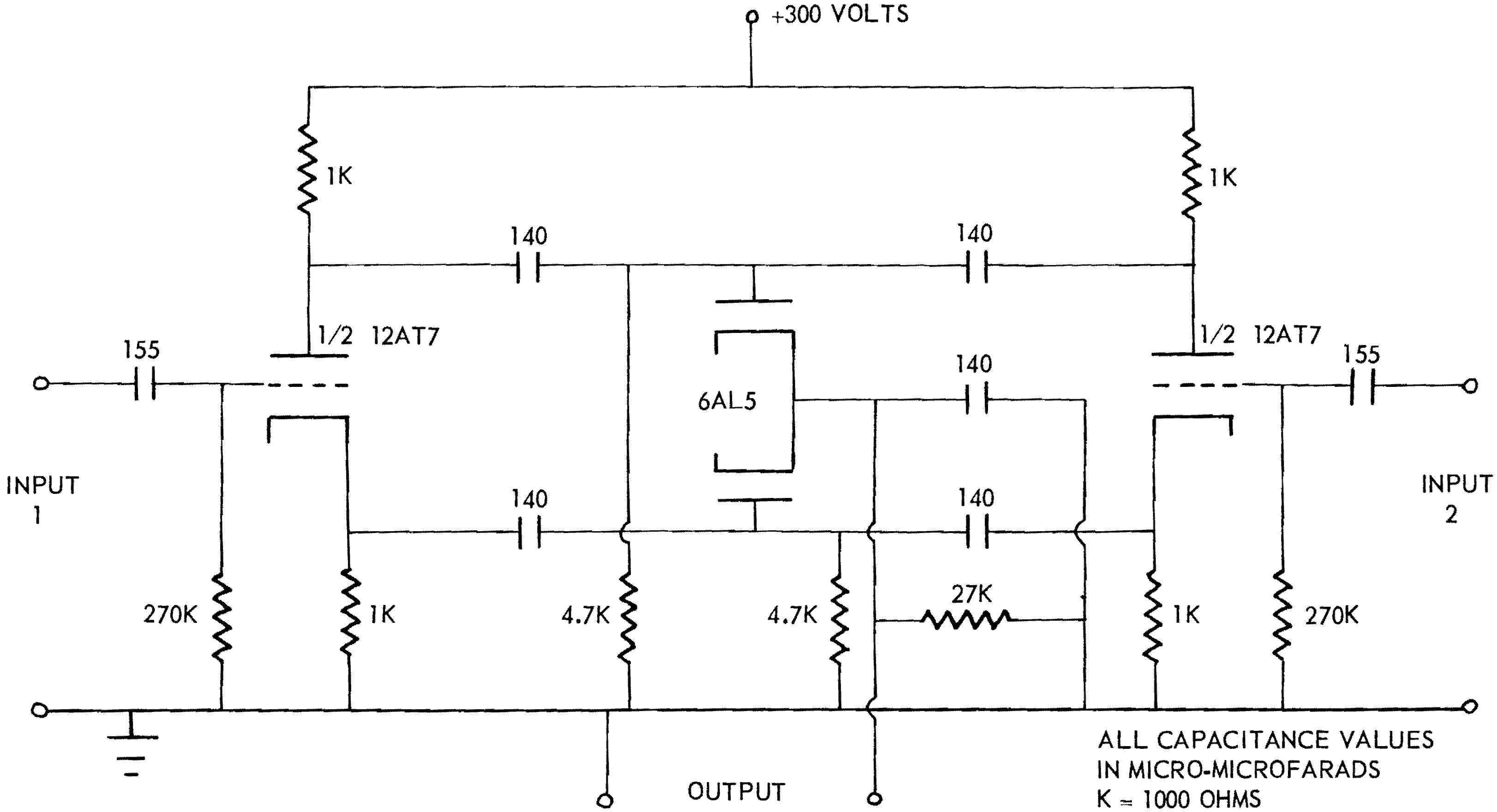


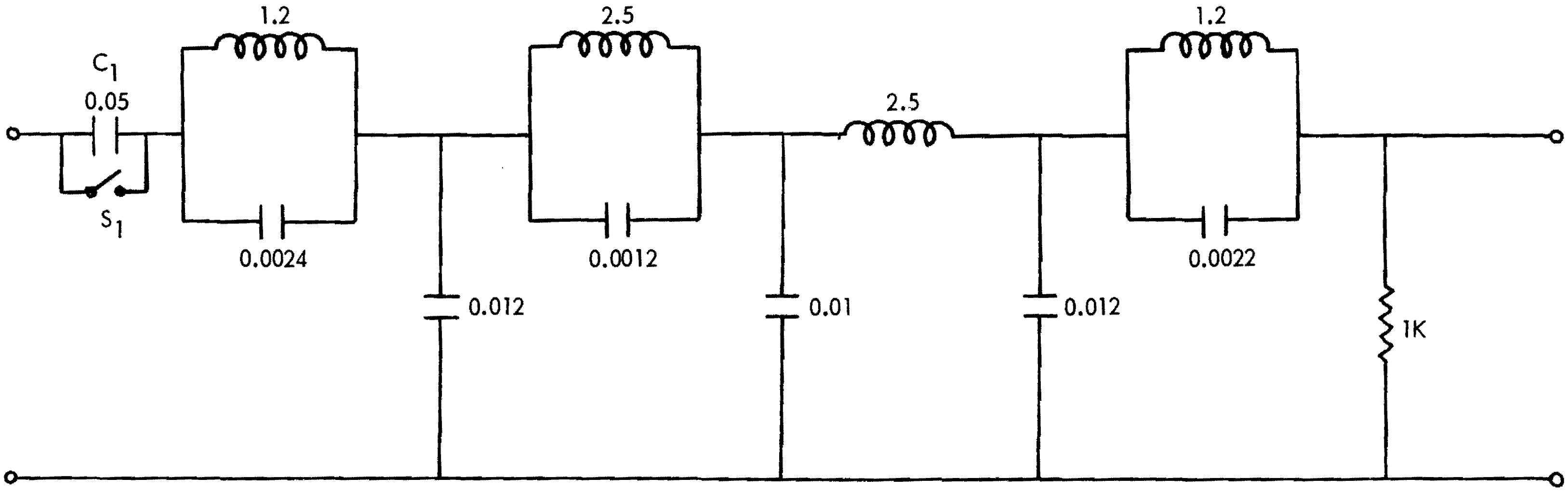
Figure 20. Circuit Diagram of the Mixer.

substantial cancellation of the input frequencies. The mixer is followed by the low pass filter shown in Figure 21. The filter is m-derived and provides the attenuation characteristic shown in Figure 22. The characteristic impedance of the filter is approximately 500 ohms. The Capacitor, C_1, and Switch, S_1, were included to provide optional attenuation of 60 cycles per second and low-frequency noise voltages.

The output from the filter is amplified by the circuit shown in Figure 23. Shown also in this figure are the base connections of the Confluxer. The Confluxer is a commercially constructed constant-magnetic-charge device resembling a magnetically-coupled one-shot multivibrator. The time integral of the output pulses is reasonably independent of the input voltage waveform and repetition rate. The output integral varies only about 1 percent for extreme changes in tube characteristics and supply voltages. The Confluxer uses a 12AT7 vacuum tube and requires a plate supply voltage of between 200 and 300 volts.

The output of the Confluxer is magnetically coupled and thus must be detected to obtain a d-c voltage proportional to input frequency. The detector diagram is included in Figure 23. The R-C elements following the detector provide some filtering to smooth the d-c output of the detector. A greater degree of filtering cannot be used at this point since the resulting phase characteristics would produce an unstable condition in the overall control loop.

The filtered d-c output from the Confluxer detector is compared with an adjustable voltage from a battery biased Helipot by the circuit shown in Figure 24. The circuit is a conventional differential amplifier and provides an amplification of the error voltage by a factor of approximately 35. The output of the differential amplifier drives a cathode follower, also shown in Figure 24, which provides the low impedance source for the frequency-modulation input of the Marconi Signal Generator. Three type NE-2 neon lamps are used as



ALL CAPACITANCE VALUES IN MICROFARADS.
INDUCTANCE VALUES IN MILIHENRIES.
K = 1000 OHMS

Figure 21. Circuit Diagram of the Low-Pass Filter.

coupling between the differential amplifier and the cathode follower to correct the d-c level of the output without signal attenuation.

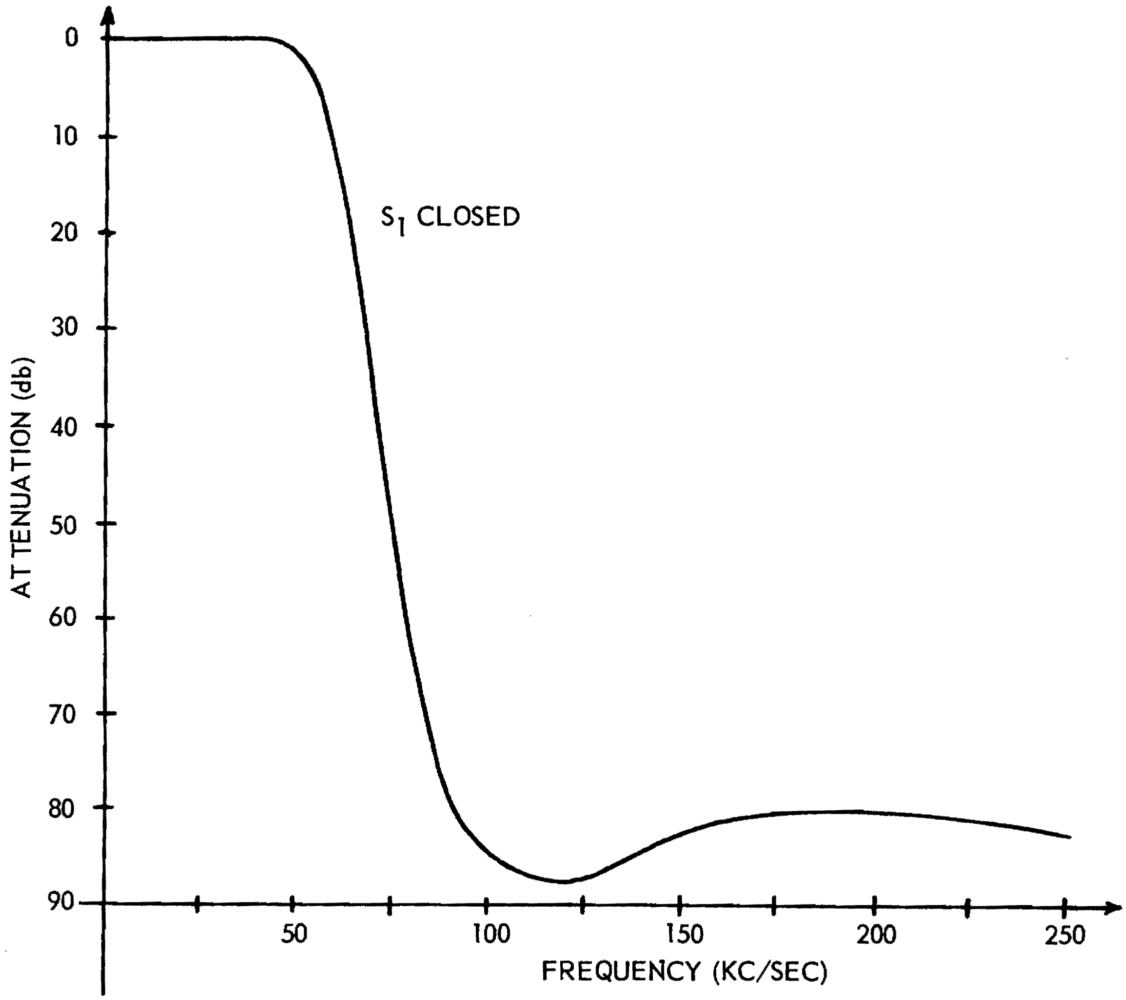


Figure 22. Attenuation-Versus-Frequency Characteristics of Low-Pass Filter.

The equipment which has been described has been breadboarded and tested to determine the system characteristics. The overall open-loop gain is between 30 and 40. An improvement in the stability of the Marconi Signal Generator by this factor would be expected when the loop is closed. Such an improvement in short-term stability and microphonic stability was observed. The improvement

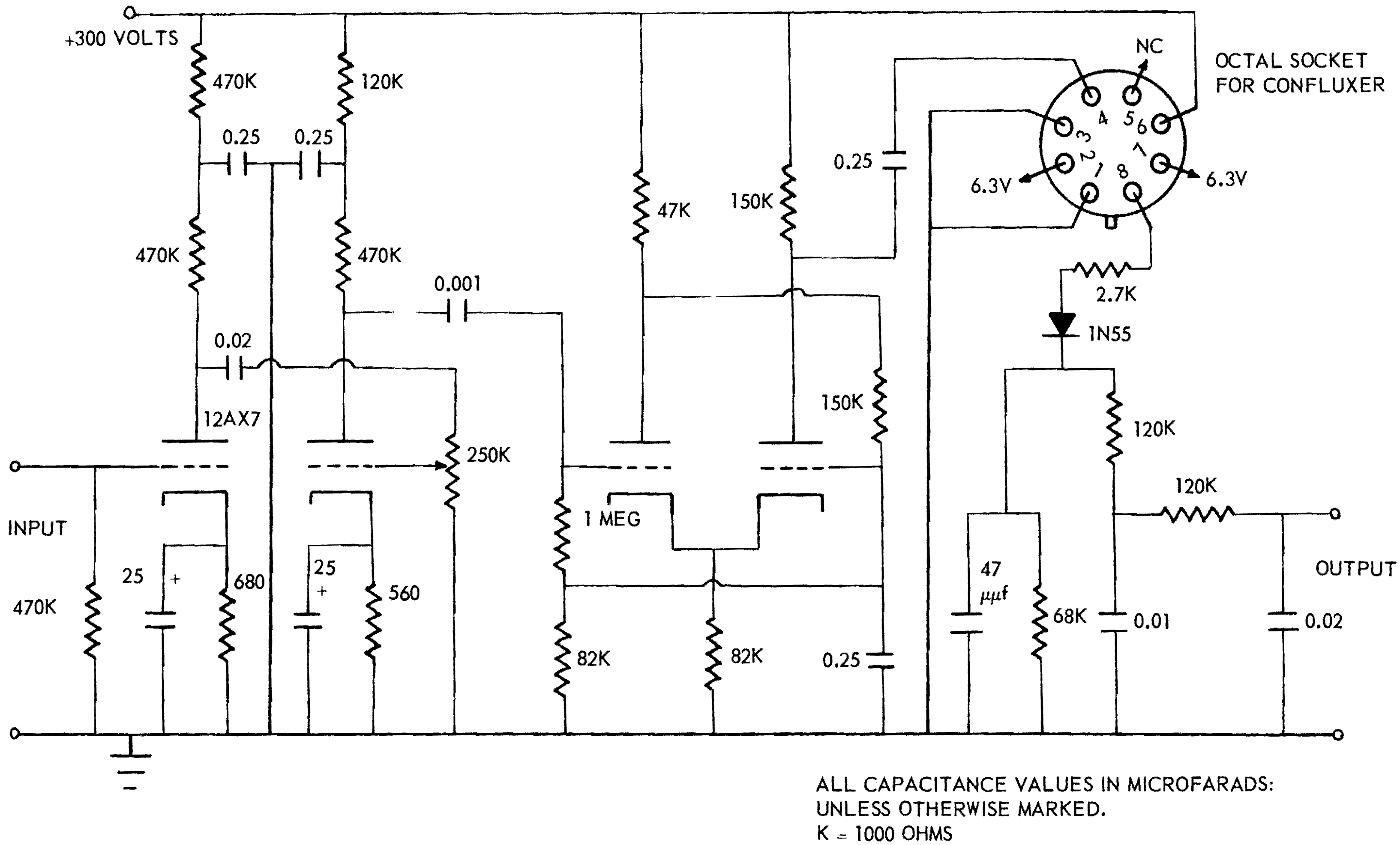


Figure 23. Circuit Diagram of the Preamplifer, Detector, and Filter.

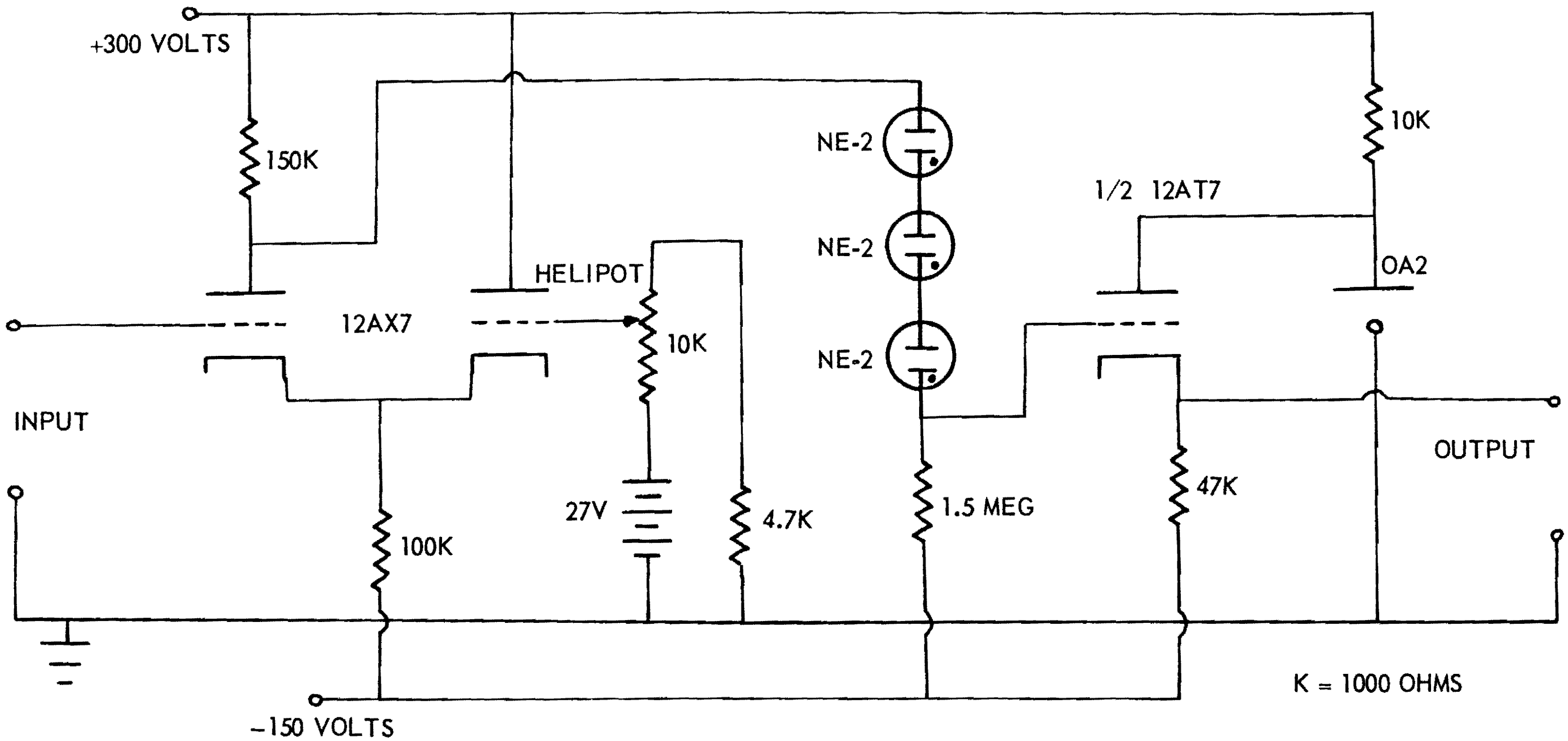


Figure 24. Circuit Diagram of the Differential Amplifier, Reference Standard, and Cathode Follower.

in longer-term stability, over a period of several minutes, was by a factor of approximately 10. The reduction in improvement over the longer period of time appeared to be the result of drift in the Confluxer and differential amplifier.

With the servo system in operation, the frequency of the Signal Generator could be adjusted to within 10 cycles per second of any desired frequency by using the Helipot as a fine-tuning control.

Some components of the system have been constructed in their final form while others are still in breadboard form. The construction of the final units is being continued.

4. Determination of Crystal Q from Substitution Measurements

One of the more important parameters of high-frequency crystals is the quality factor, Q. The other important parameters can be measured directly with the substitution system; however, the Q can be determined only through fairly complicated calculations.

A principal difficulty in measuring Q is first encountered in defining the quantity for a circuit which cannot be represented by a simple series resonant circuit. The Q can be defined in terms of stored and dissipated energies; however, a more appropriate definition of Q for a crystal appears in terms of the phase angle as a function of frequency. The quantity, $d\theta/df$, at a point of zero susceptance, is indicative of expected oscillator stability and will be accepted as the basis for the definition of Q. Thus, for a high-frequency quartz crystal, Q will be defined as:

$$Q = \frac{f_o}{2} \cdot \frac{d\theta}{df}\bigg|_{\beta = 0} ,$$

where θ is the phase angle of the crystal admittance.

For measurement purposes, $d\theta/df$ must be approximated by $\Delta\theta/\Delta f$. If Δf is kept small, little error is introduced. To determine the error magnitude for a typical crystal, a theoretical typical crystal characteristic was plotted on a rectangular coordinate as shown in Figure 25. The actual Q was calculated from the slope of a curve of phase angle versus frequency (not shown). The values of Q for various combinations of data points are indicated by the connecting lines in the figure.

For the determination of the Q of a crystal, G_{max} and G_{min} are first determined as described in the Interim Report. If a substitution resistor with a conductance G_k, less than G_{max} and greater than G_{min}, is placed in the component mount and the shorted stub is adjusted as for conductance determinations, curve C of Figure 26 is obtained for the sweep mode of operation. This curve is observed to be a straight line. If the position of the line is marked on the display and if the resistor is replaced by the crystal, curve D is obtained after proper adjustment of the shorted stub. Points A and B represent the intersections of the two curves. The frequencies at points A and B may be determined by reducing the sweep to zero deviation at these points.

Figure 27 shows the admittance function of the antiresonated crystal plotted on rectangular coordinates. Points A and B correspond to the curve intersections of Figure 26. The approximate Q of the crystal can be determined by calculating θ of Figure 27 since the frequencies at points A and B are already known, The angle, θ, however, is a function of three quantities, G_{max}, G_{min}, and G_k. For any given value of G_k, a family of curves can be constructed from which θ, as a function of G_{max} and G_{min}, can be determined. Since approximately 25 values of substitution resistors are presently available, 25 families of curves would be required to determine Q for a random selection of G_k.

An alternate procedure for determining θ would be to select G_k as some specified function of G_{max} and G_{min} so that only one family of curves would be required. The equation for θ, which may be derived from Figure 27, is

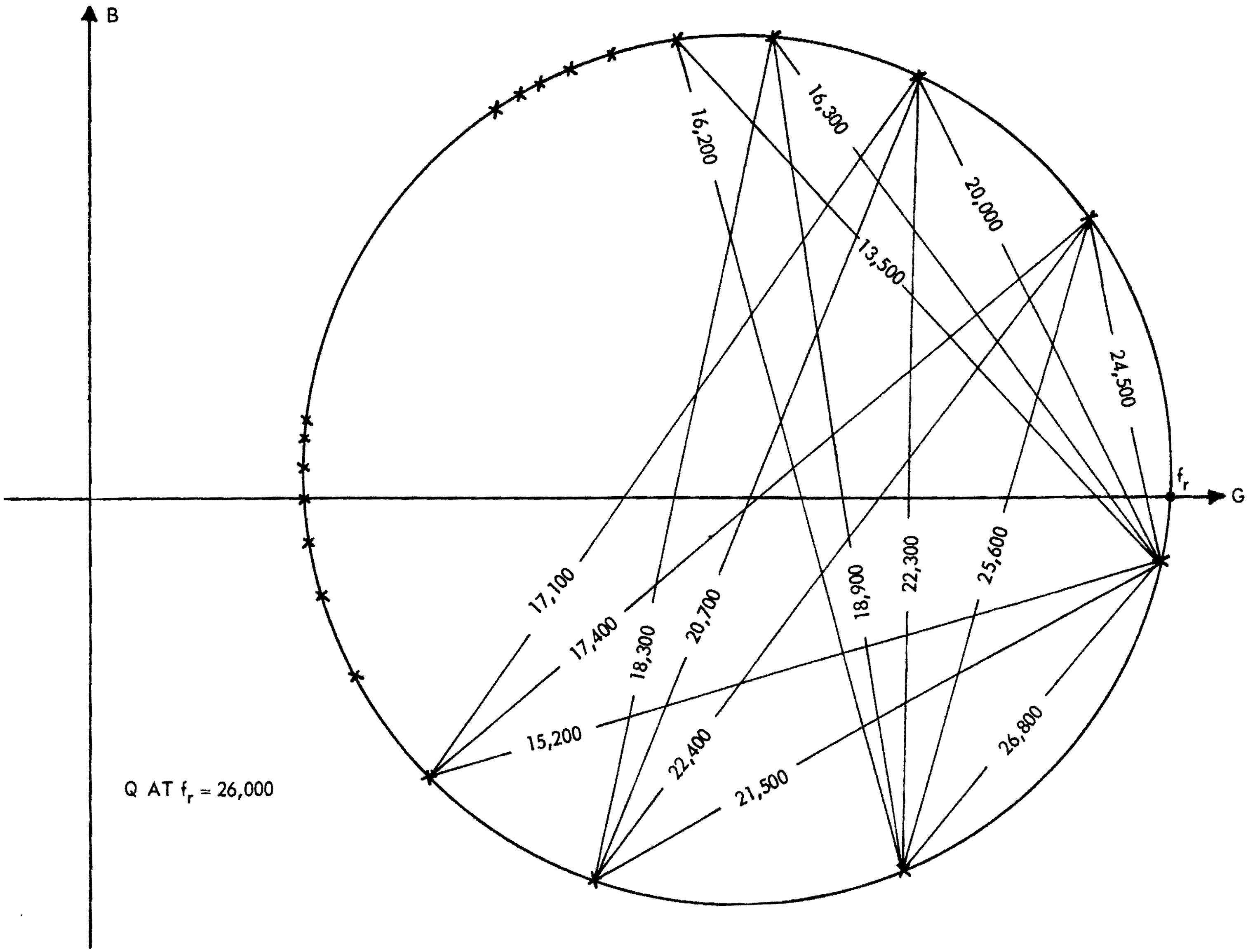


Figure 25. Q Approximations for a Theoretical Crystal at 300 Mc/Sec.

$$\theta = \mathrm{Cos}^{-1} \frac{G_k^{\,2} + 40\ G_k + G_{max}\ G_{min}}{\sqrt{G_{max} + G_{min} + 40\sqrt{(G_{max} + G_{min})(G_k^{\,2} + 40\ G_k + G_{max}\ G_{min}) - 40 G_{max}\ G_{min}}}} .$$

For good accuracy in determining θ, the angle ϕ of Figure 27 should be between 30 and 90 degrees. Theoretical studies have shown that, for typical crystals, ϕ will be restricted to angles between 45 and 55 degrees if $G_k = 0.85\ G_{max} + 0.15\ G_{min}$. Also, the equation for θ may now be expressed in terms of two variables, G_{max} and G_{min}, and and only one family of curves is required. This family of curves is shown in Figure 28. A quality factor, Q' , may now be defined as:

$$Q' = \frac{f_o}{2} \cdot \frac{\Delta\theta}{\Delta f}$$

where $\Delta\theta$ is two times the value of θ as determined from the curves of Figure 28 and Δf is $(f_B - f_A)$. The quantity Q' will differ from the defined Q by a relatively constant percentage since the angle ϕ remains nearly constant under the chosen condition for G_k.

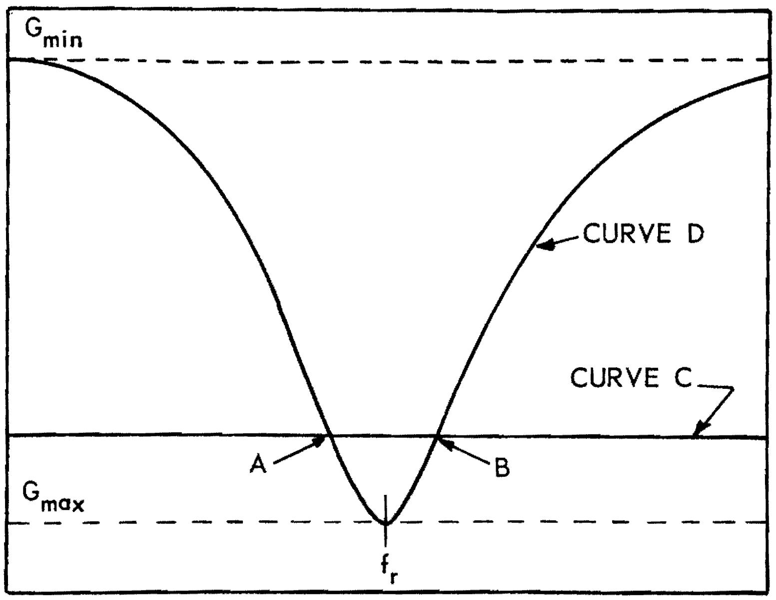


Figure 26. Sweep Display with the Substitution Measurement System.

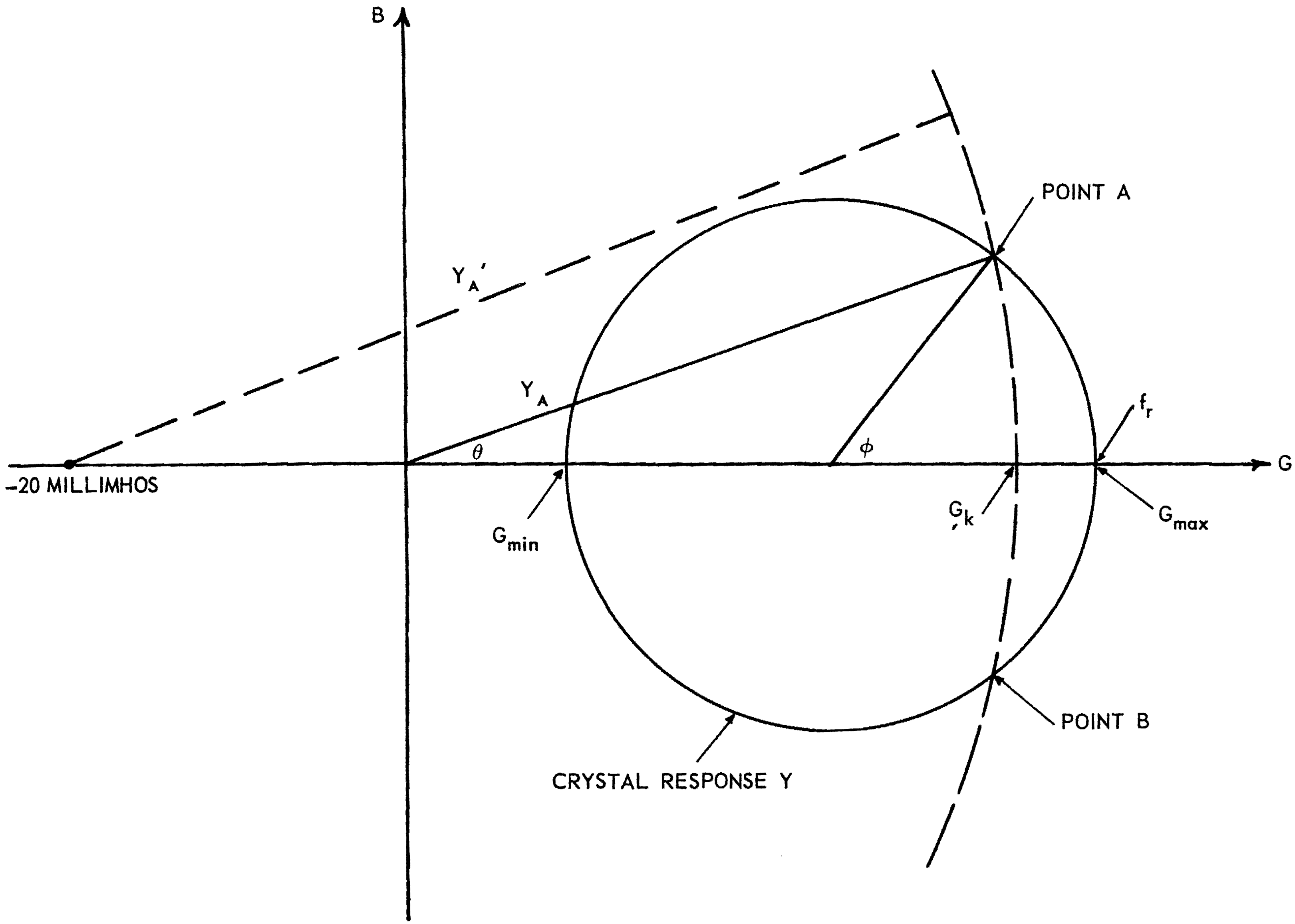


Figure 27. Admittance Vector Diagram for the Substitution Measurement System.

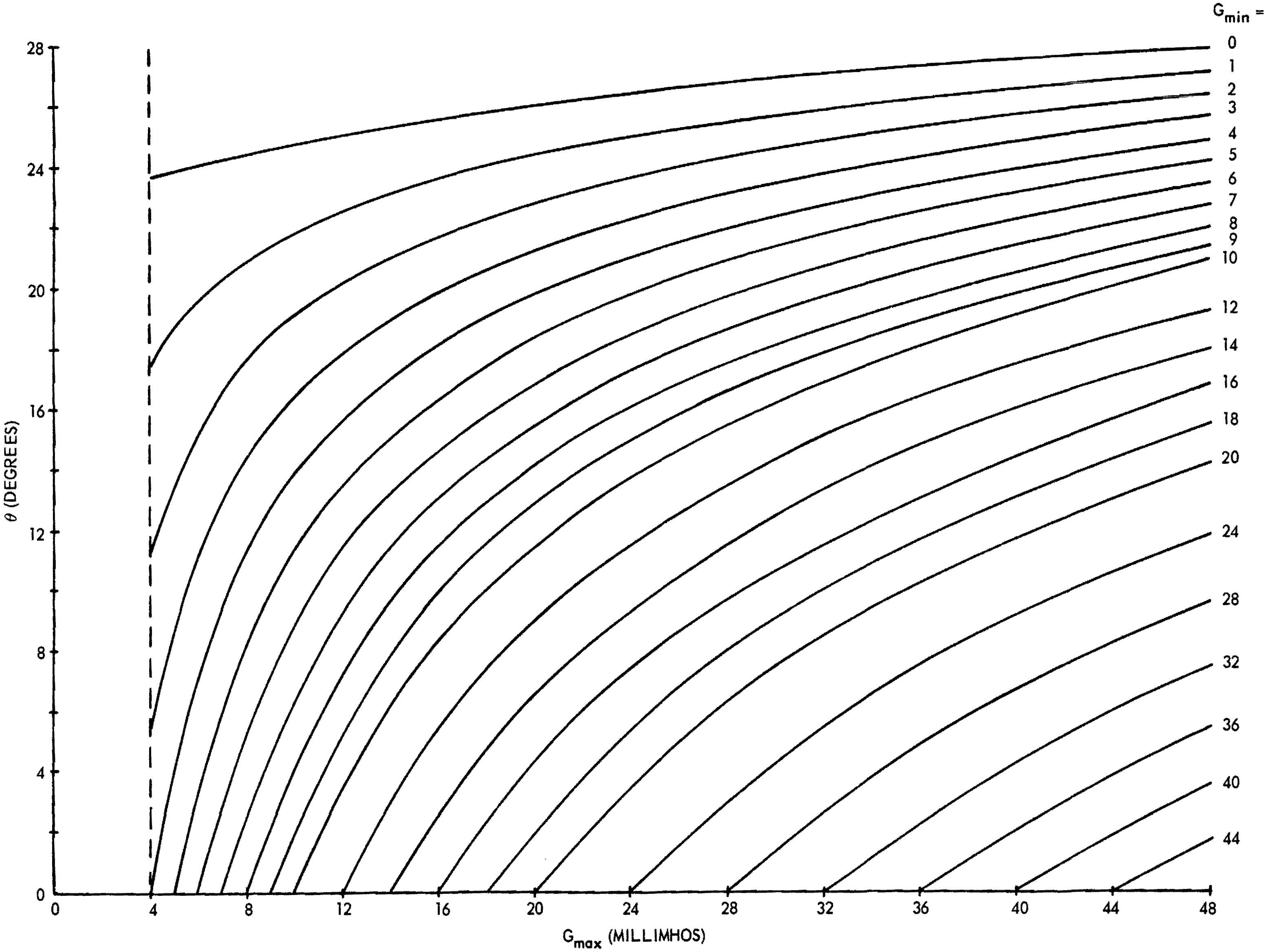


Figure 28. θ-Curves for $G_k = 0.85\ G_{max} + 0.15\ G_{min}$.

If the overtone response of a crystal is not a perfect circle with symmetrical frequency distribution, additional errors in Q determination will be introduced. Spurious responses close to the main response can readily produce such errors.

Laboratory testing of this Q determination procedure has been delayed until the Marconi Signal Generator stabilization system can be completed.

5. Computer Programs

In the performance of this and previous contract work, extensive use has been made of digital computers for the more complicated mathematical computations. Transmission line subtraction, crystal parameter calculation, and other programs were written and have been regularly used. Floating point numerical representations were necessary because of the range of values of some of the quantities. The required mathematical calculations included sums, differences, quotients, products, square roots, sines, cosines, tangents, arc-sines, arc-cosines, arc-tangents and other special functions. The available computers were capable of none of these operations in floating point arithmetic.

Basic machine language could have been used in writing the programs in which case the necessary floating point operations would have been written into the programs. The writing of each program would, however, have required several man-days. Instead, the programs were written in the language of the Bell General Purpose Interpretive System for the IBM-650 computer. The required orders were relatively few and simple since all of the necessary floating point operations were already written into the Bell System. The personnel time required for writing the programs was generally only a few minutes per program; however, the machine running time was often several times as great as would be required for optimum machine-language programs.

During this report period, a new IBM-650 system known as "Revised Unified New Compiler with IT-Basic Language Extended" (RUNCIBLE) was received by the computer center. In the RUNCIBLE system the computer is used to convert normal mathematical equations into optimum machine language programs. The machine-language program is then available for use at any time. Although the conversion is relatively slow, the operation of the machine-language program is very fast. Furthermore, the time required in writing the programs for RUNCIBEL (simply copying the mathematical equations in a special format) was negligible.

Since the anticipated need for computer time for analyzing the Crystal Measurements Standard System and the substitution crystal measurement system had increased substantially, several of the most used programs were rewritten into RUNCIBLE. The instruction book stated that the trigonometric tangent operation was included in the RUNCIBLE packages; however, each test of the new programs failed in the calculation of this function. Four man-weeks of studies and tests finally indicated that the tangent operation had been omitted by the writers of the RUNCIBLE system. With some of the programs, the sine and cosine operations were substituted for the tangent operations; however, the resulting programs did not prove to be appreciably faster than the corresponding Bell System programs.

The RUNCIBLE system is currently being used for some of the computer calculations. For example, the curves of Figure 28 were calculated by a RUNCIBLE program.

C. Phase III. Aging of Quartz Resonators

1. Introduction

This phase of the work, assigned the Project Number A-402-13 by the Engineering Experiment Station of Georgia Institute of Technology, was initiated on 1 March 1959 and is a continuation of the work prior to that date under Contract No. DA-36-039 SC-78910, Georgia Tech Project No. A-402-3. The work undertaken on 1 March under Contract No. DA-36-039 SC-78905, was subsequently expanded under modification No. 1 to the Contract and renewed for an additional period of 12 months starting 1 July 1959, under Modification No. 4.

Investigation of the aging of 16.25 mc AT-cut quartz resonators procured from industrial sources and stored at 25°, 85°, and 125°C were completed; studies of similar units fabricated here in glass containers were continued.

The task of setting up a frequency measuring system for quartz resonators of 100 mc/sec frequency has been completed. The associated ovens for storage of units at 0° and 55°C for cycling between those temperatures are near completion. Resonator blanks for 100 mc/sec operation have been obtained, but no resonators have yet been fabricated. These studies are to begin within the next 15 days.

2. Apparatus

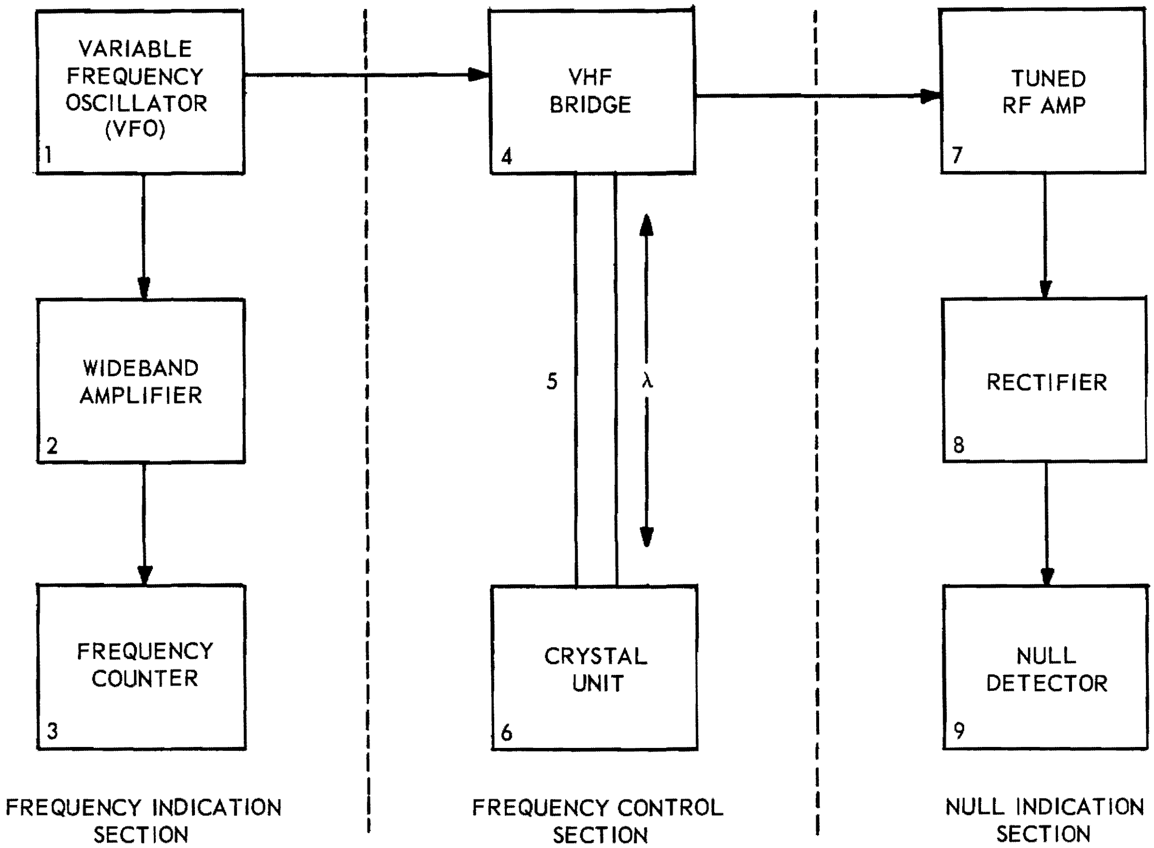
a. Frequency Measuring System for 100 Mc/Sec Resonators. The measurement of the frequencies of a number of 100 mc/sec resonators daily, with a precision of $\pm$ 2 parts in 10^8, required the design and construction of a frequency measuring system of the specified accuracy and a reasonable speed in making measurements. Likewise, ovens for accurate temperature control of resonators stored at specific temperatures of 0° and 55°C and cycling between these temperatures were necessary. The construction of the frequency measuring system and associated ovens are described below.

The frequency measuring system consisted of an oscillator, the CI Meter TS-15 (or equivalent), for driving the crystal, a VHF bridge and associated instruments for adjusting the crystal to resonance by means of a null detector, an amplifier and a frequency counter. A block diagram of the system is shown in Figure 29 and the laboratory set-up in Figure 30. The VHF bridge and the rectifier (Item 8 of Figure 29) were constructed here. For connection to resonators in ovens a tuned coaxial line to the resonators also was required.

(1) The VHF Bridge. The frequency control section (consisting of the VHF bridge, the resonant twin-coaxial transmission line and the crystal) is the heart of the frequency measuring system. The other sections utilize or display information derived from this section.

The final circuit of the VHF bridge is illustrated in Figure 31. The physical appearance of the bridge is shown in Figure 32. Although the circuit is not unique, the construction represents a radical departure from that used for radio frequency bridges previously designed and built at Georgia Tech. Each of the four bridge impedances and the output transformer were placed in separate compartments of the chassis. It was found that coupling between the various bridge components could thereby be materially reduced with a corresponding increase in the bridge sensitivity. For maximum repeatability, the tuning shafts of the VFO and variable condenser C_1 (Figure 31) were driven by 40-to-1 anti-backlash reduction gears. The coaxial line from the bridge to the null amplifier was further shielded by placing the line inside a copper tube. The bridge and other components of the frequency measuring equipment have been assembled on a standard 19-inch rack as illustrated in Figure 30. All equipment in the rack obtains power through a constant voltage transformer. The equipment rack and the frequency counter were mounted on wheels to facilitate moving to the various test positions in the laboratory.

Although a detailed study of the performance of the VHF bridge has not been made, the performance was assessed by repetition and by comparison of frequency measurements made with the VHF bridge with measurements made on the same 100 mc/sec crystals by other means.



1. TS-15 (OR EQUIVALENT)
2. IFI MODEL 530
3. HEWLETT-PACKARD MODEL 524C
4. VHF BRIDGE (See Text)
5. FULL WAVE (100 MC) TWIN-COAXIAL LINE
6. CRYSTAL UNIT FOR TEST
7. VHF RECEIVER, SERVO MODEL R-5200
8. RECTIFIER (See Text)
9. HONEYWELL MODEL 104W1G

Figure 29. Block Diagram of the Frequency Measuring Equipment for 100 Mc/Sec.

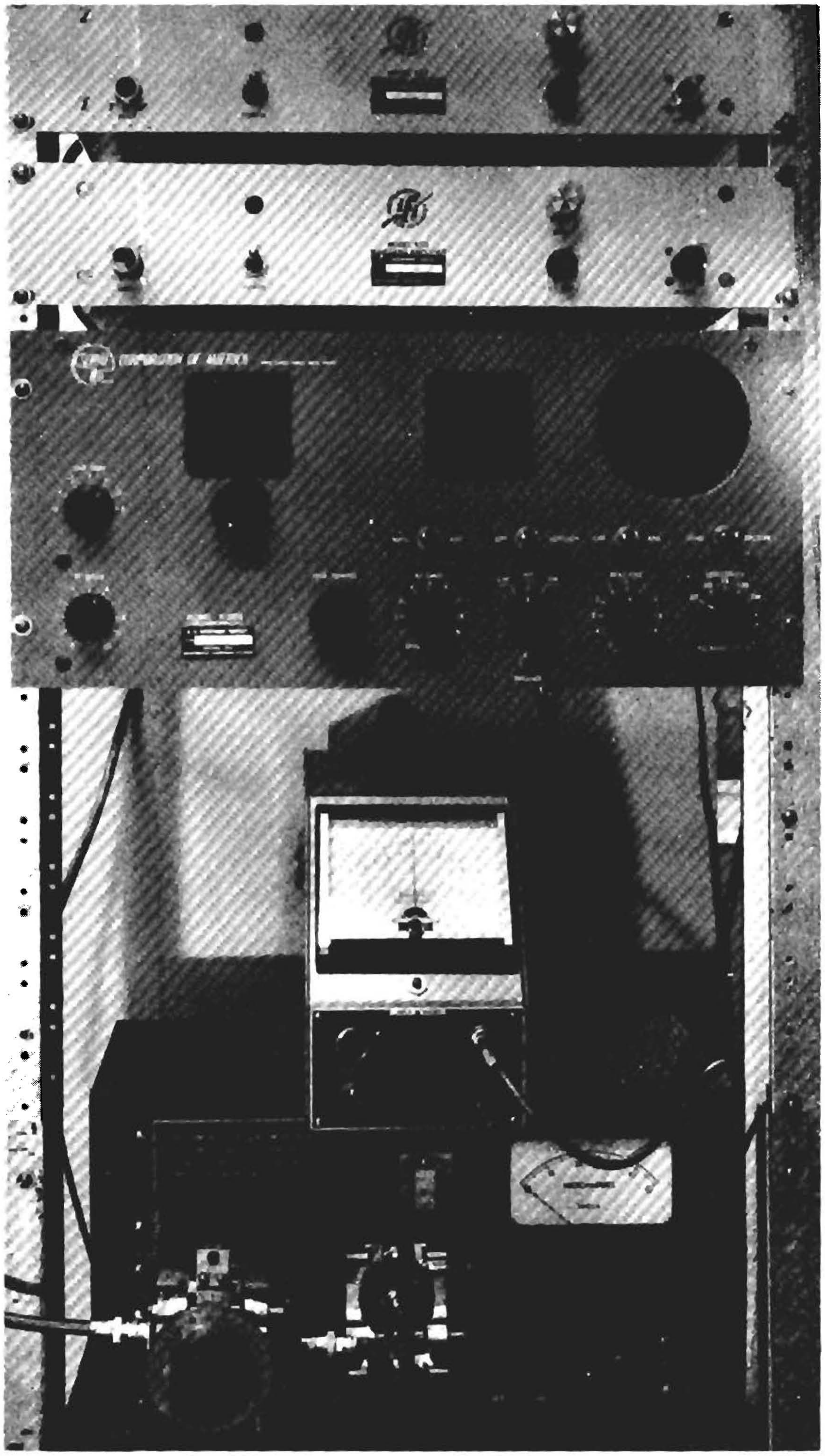
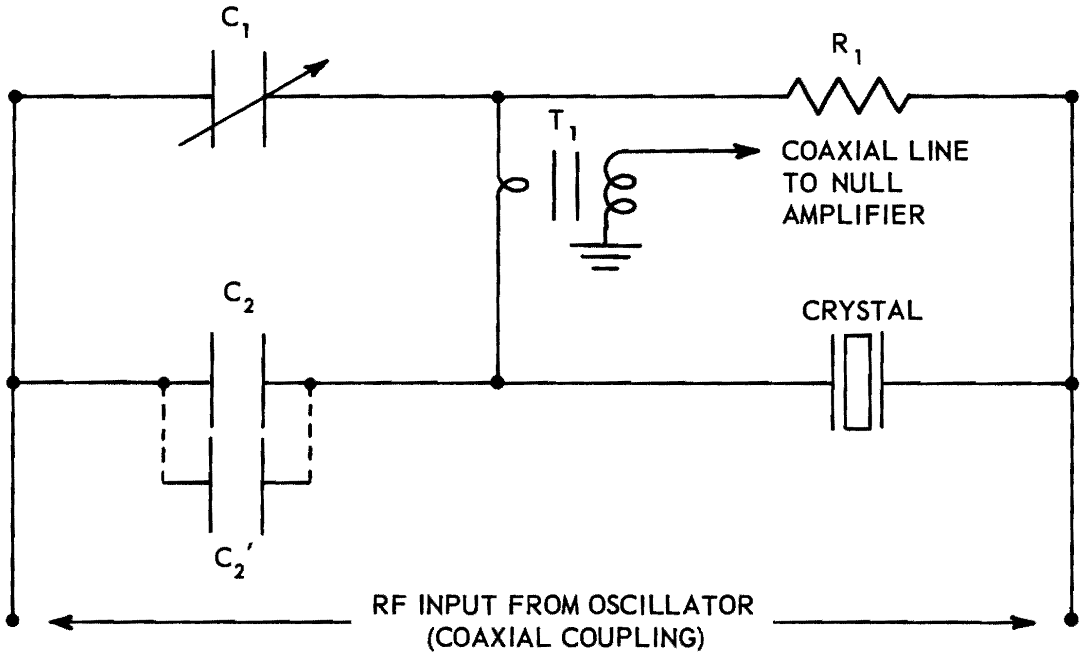


Figure 30. Frequency Measuring Equipment for 100 Mc/Sec.



C_1 – AIR DIELECTRIC 2.7 TO 19.6 $\mu\mu f$
C_2 – SILVERED MICA 10 $\mu\mu f$
C_2' – SILVERED MICA 15 OR 40 $\mu\mu f$ (See Text)
R_1 – COMPOSITION 120 Ω
T_1 – ONE TURN PRIMARY, TWO TURN SECONDARY, FERRITE CORE
CRYSTAL – PROVISION MADE FOR OPERATION DIRECTLY INTO BRIDGE OR AT END OF FULL WAVE TWIN-COAXIAL LINE

Figure 31. Circuit for VHF Bridge for 100 Mc/Sec.

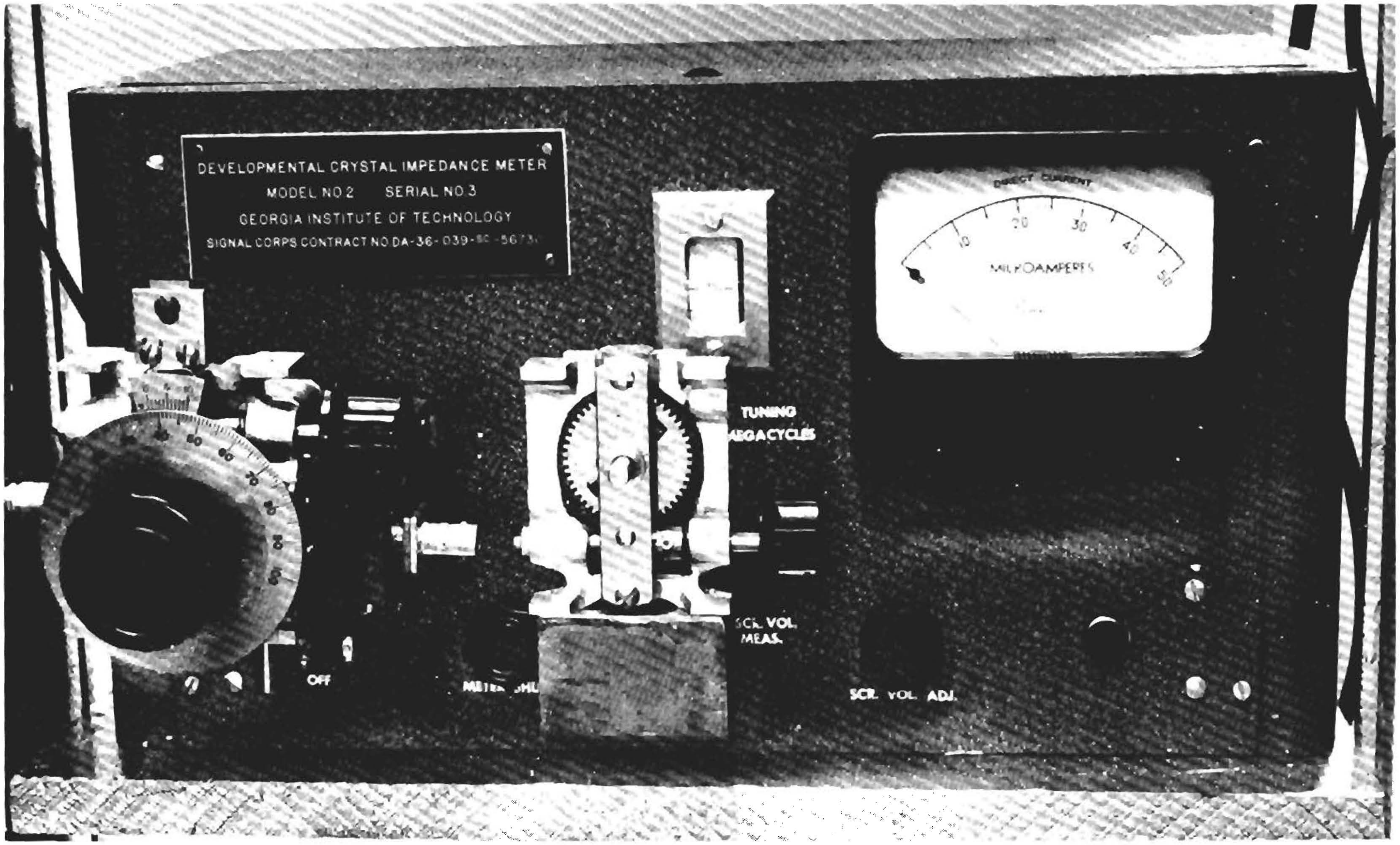


Figure 32. Variable Frequency Oscillator (VFO) and VHF Bridge.

The relations at balance for the circuit of Figure 31 follow:

$$\frac{X_{c_1}}{R_1} = \frac{X_{c_2}}{R_s} \text{ , or } R_s = \frac{X_{c_2} R_1}{X_{c_1}} \text{ ohms} \qquad (1)$$

Since the phase angles of the impedances are

$$\tan^{-1} \phi_s = \frac{X_{c_1}}{R_1} \text{ for the shunt branch} \qquad (2)$$

and

$$\tan^{-1} \phi_c = \frac{X_{c_2}}{R_2} \text{ for the crystal branch,} \qquad (3)$$

the branch currents must be in phase. Thus, provided the conditions established by (1) can be realized, a balance should be obtained with respect to both the magnitude of the bridge impedances and the phase of the branch currents.

The balance range of C_1 was then determined. An air dielectric trimmer having a range of 2.7 to 19.6 μμf was selected for C_1. Therefore C_1 = 590 ohms (max), 80 ohms (min) at 100 mc/sec.

When C_2 = 10 μμf (X_{c_2} = 160 ohms) the range of R_s values which satisfy (1) are then 240 ohms (max) and 33 ohms (min). Although it appeared that such a range of R_s values would be adequate, it was found by experiment that stray reactances modified the calculated range to the extent that it was necessary to pad C_2 in order to cover the lower resistance end of the anticipated R_s range. Silvered mica capacitors of 15 and 40 μμf were each mounted in HC-6/U crystal holders and used as a plug-in to increase condenser C_2. With effective values of 10, 25, or 50 μμf for C_2, this arrangement satisfied the balance equations for R_s values from about 10 ohms to over 250 ohms.

At the time of construction only a few 100 mc crystals (5th overtone units) were available for measurements. Table I gives the information obtained during measurement of the frequencies and resistances of four of these crystals by three methods. It should be noted that the crystals were plugged directly into the VHF bridge, since the full wave transmission line was not used for this comparison study. The excellent sensitivity and repeatability of the VHF bridge was apparent during the experiment. The bridge was adjusted to within ± 2 cycles of the indicated frequency on repeated trials.

TABLE II

COMPARISON OF MEASUREMENTS OF FREQUENCY AND RESISTANCE

Crystal No.	VHF Bridge* Frequency (Cycles)	VHF Bridge* C_1 Dial Setting	A-151 Bridge** Frequency (Cycles)	A-151 Bridge** R_s (ohms)	CI Meter Substitution Frequency (Cycles)	CI Meter Substitution R_s (ohms)
1	100 001 700	48.5	100 001 866	45	100 001 929	58
2	100 000 455	11.0	100 000 528	24	100 001 470	38
3	99 998 556	42.0	99 998 595	39	99 999 096	55
4	100 000 582	36.5	100 000 644	35	100 001 239	55

NOTE: C_o was not compensated. A compensated VHF rheostat was used for the measurements made with the A-151 bridge and for the CI meter substitution measurements.

* C_2 = 25 μμf

** Bridge developed under Contract No. DA-36-039 SC-71191.

A complete calibration curve of the C_1 dial versus R_s will be made when more 100 mc crystal units are available.

(2) The Coaxial Connector Line. The full wave twin coaxial line with BNC terminations at each end was then adjusted to length. The previously measured crystals were connected to the ends of lines known to be too long and the frequencies and resistances (C_1 dial setting) were again measured. All measurements were made with the bridge at balance. The lines were then shortened

by known amounts until the crystal frequencies and resistances agreed as closely as possible with the original measurements in the bridge. With a little practice the frequencies can be made to agree within 5 parts in 10^7, and the resistances can be made to agree to within 5%. Impedance matching units inserted into the lines to accomplish the electrical adjustment of the line length did not afford the desired precision of adjustment and were discarded.

(3) The Rectifier. The rectifier (No. 8, Figure 29) consists of a simple diode circuit for rectification of the 5 mc/sec I-F output of the receiver to a form suitable for driving the null detector, a Minneapolis-Honeywell Model 104 WIG.

(4) Comments. The measurement and control of the amplitude of vibration of the crystal units being measured presented a problem. The differential VTVM Model ME-56/TSM used to measure the voltage across crystals at 16.5 mc/sec was not suitable for use at 100 mc/sec. Automatic gain control for the VFO was applied to the control grid of one of the amplifier tubes. This action did not provide sufficient control. It was then found that a small change in screen voltage had far greater effect than a relatively large change in control grid voltage.

The application of AGC to the screen grid presented an attractive possibility; another solution to the problem of the control of the amplitude of oscillation was tried with excellent success for the few 100 mc/sec crystals available for testing. Consider the arrangement shown in Figure 33. The voltages at points A and B can be measured with good accuracy using a Millivac Model MV-18BRF VTVM. The voltages cannot of course be subtracted directly to obtain the voltage across the bridge due to the phase relations existing at A and B. It was found that it was not necessary to measure both voltages to obtain a constant amplitude of crystal vibration. When the voltage at A is held constant at some predetermined value by controlling the screen voltage, the crystal frequency may be adjusted to within 2 parts in 10^8 on repeated measurements. The optimum value of the voltage at A was found to be 25 mv. This value is obtained at a screen voltage of about 10 volts.

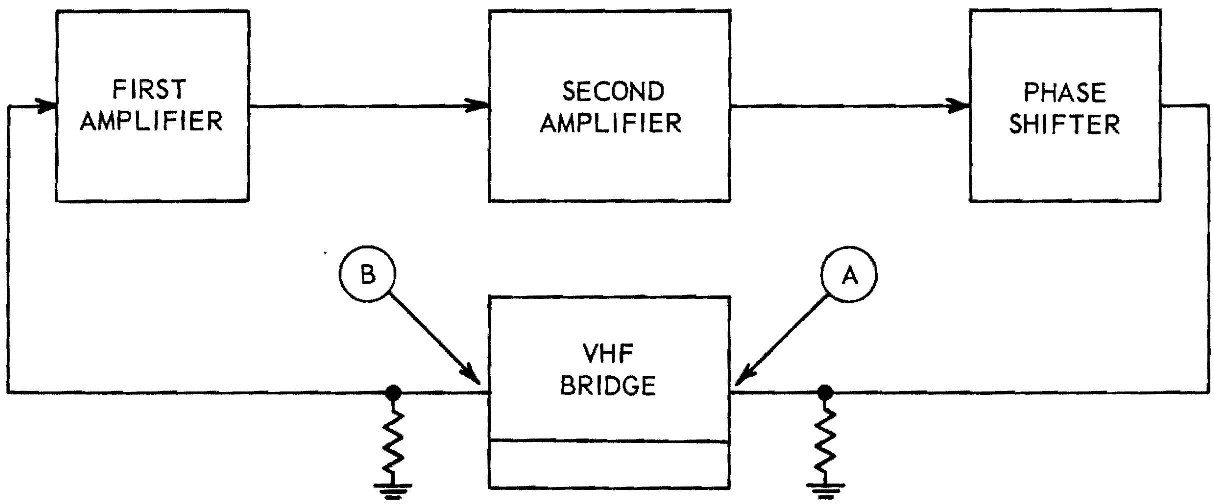


Figure 33. Functional Schematic Diagram of Oscillator and VHF Bridge.

Accurate measurement of crystal aging requires that the amplitude of crystal vibration have a low and constant value. The technique described apparently gives a constant value. It is conjectured that the crystal power is also very low for two reasons. First, the oscillator is operated at very low gain, i.e., a reduction of the screen voltage from 10 volts to about 8 volts causes oscillation to stop. Secondly, when a crystal unit is tuned to null no stabilization period is required before the measurements of frequency can be made. When somewhat higher drive levels are used (i.e., higher voltage at

Point A) some time is required for the crystal frequency to reach stability. It is anticipated that the value of 25 mv at Point A will hold for all values of R_s. The required screen voltage will increase, however, as R_s increases.*

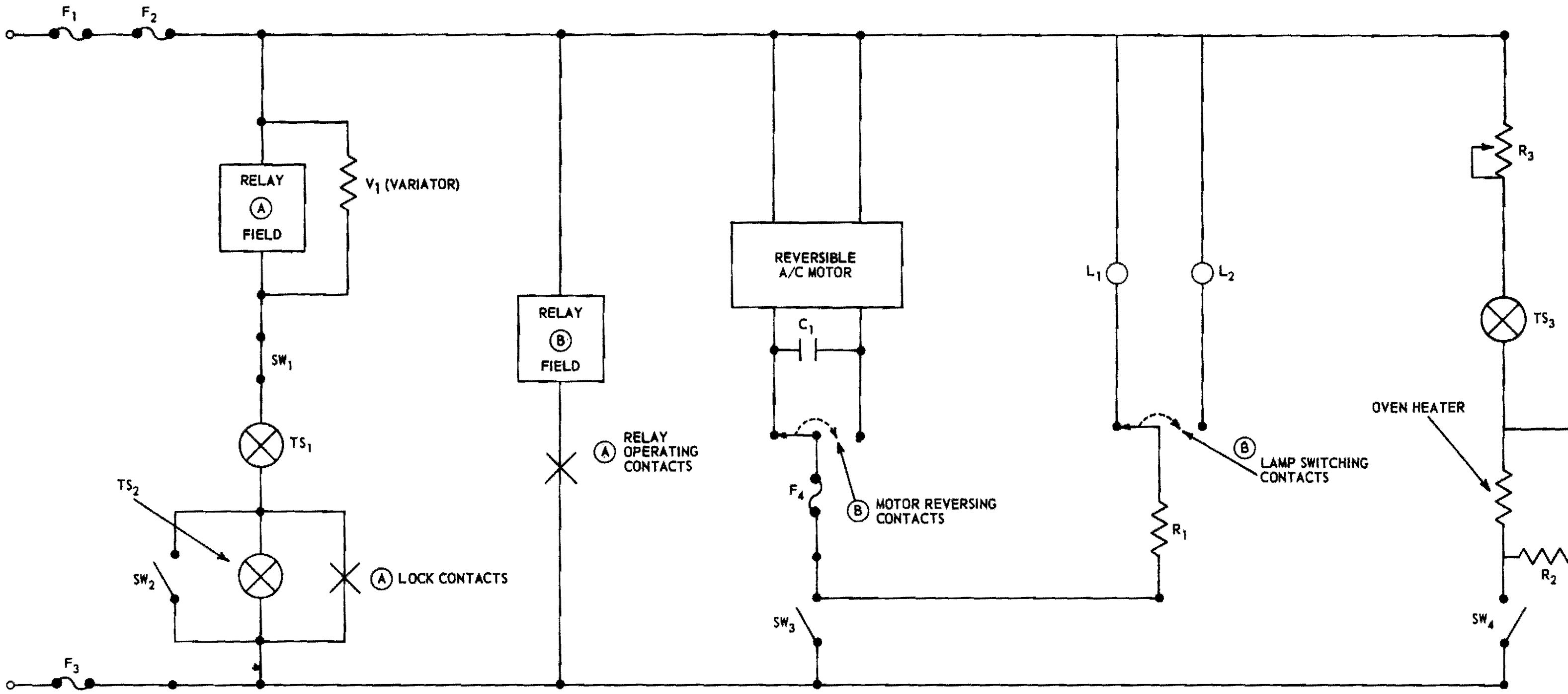
b. Resonator Aging Ovens. The temperature cycling oven and the control circuit have been completed. Final testing is being conducted to determine the proper setting of the variable speed control and the oven heater control rheostat. The control circuit schematic is shown in Figure 34. Figure 35 illustrates the oven control panel. The operation of the control circuit was covered in the last (Interim) Report.

The cycling oven consists of two nested boxes formed of 1/8" aluminum sheet. The inner box was provided with a heater on the outer vertical walls. The heater consisted of 10 turns of No. 28 gauge Chromel "A" wire bonded to the aluminum with a refractory cement. The crystals to be temperature cycled are stored in a small compartment inside of the inner box. The outer box, shown in Figure 36, has 1/4" wool felt on all surfaces. The bimetallic thermostat, the two mercury thermostats, a temperature sensitive fuse, a thermocouple and the variable-speed reduction gear are mounted on the lid of the outer box. The temperature sensing elements extend through each lid into the crystal storage compartment.

The two fixed temperature ovens (0 and 55°C) are presently under construction and the 55°C oven is nearly complete as shown in Figure 37. Each of these ovens has 36 test positions. Twin coaxial lines will be used to connect the test positions to BNC sockets mounted on the bottom of the outer box. Otherwise, the general design of the oven and control circuits will be the same as

---

* No implication is intended that all crystals would operate at the same drive level. Rather, the R-F voltage across the crystals should increase with R_s provided the voltage at Point A (Figure D) is held constant. This action need not reduce the quality of the information obtained from high resistance units provided the drive level is sufficiently low.



RELAYS
- A – SPDT (HIGH RESISTANCE FIELD)
- B – DPDT

THERMOSTATS
- TS_1 – 0°C FIXED CONTACT MERCURY
- TS_2 – 55°C FIXED CONTACT MERCURY
- TS_3 – ADJUSTABLE, BIMETALLIC

SWITCHES
- SW_1 – SPST NORMALLY CLOSED
- SW_2 – SPST NORMALLY OPEN
- SW_3 – SPST
- SW_4 – SPST

FUSES
- F_1 – 5 AMPS
- F_2 – (TEMPERATURE SENSITIVE)
- F_3 – 5 AMPS
- F_4 – 5 AMPS

RESISTORS
- R_1 – 39 K OHMS
- R_2 – 39 K OHMS
- R_3 – 25 OHMS RHEOSTAT

LAMPS
- L_1, L_2, L_3 – NE51 LAMP

NOTE: RELAY CONTACTS ARE INDICATED BY THEIR FUNCTION AND OPERATING FIELD.

NOTE: THE VARIABLE RATIO REDUCTION GEAR WHICH DRIVES TS_3 AND IS DRIVEN BY THE A/C MOTOR IS NOT SHOWN.

Figure 34. Control Circuit for Temperature Cycling Oven (0° to 55°C).

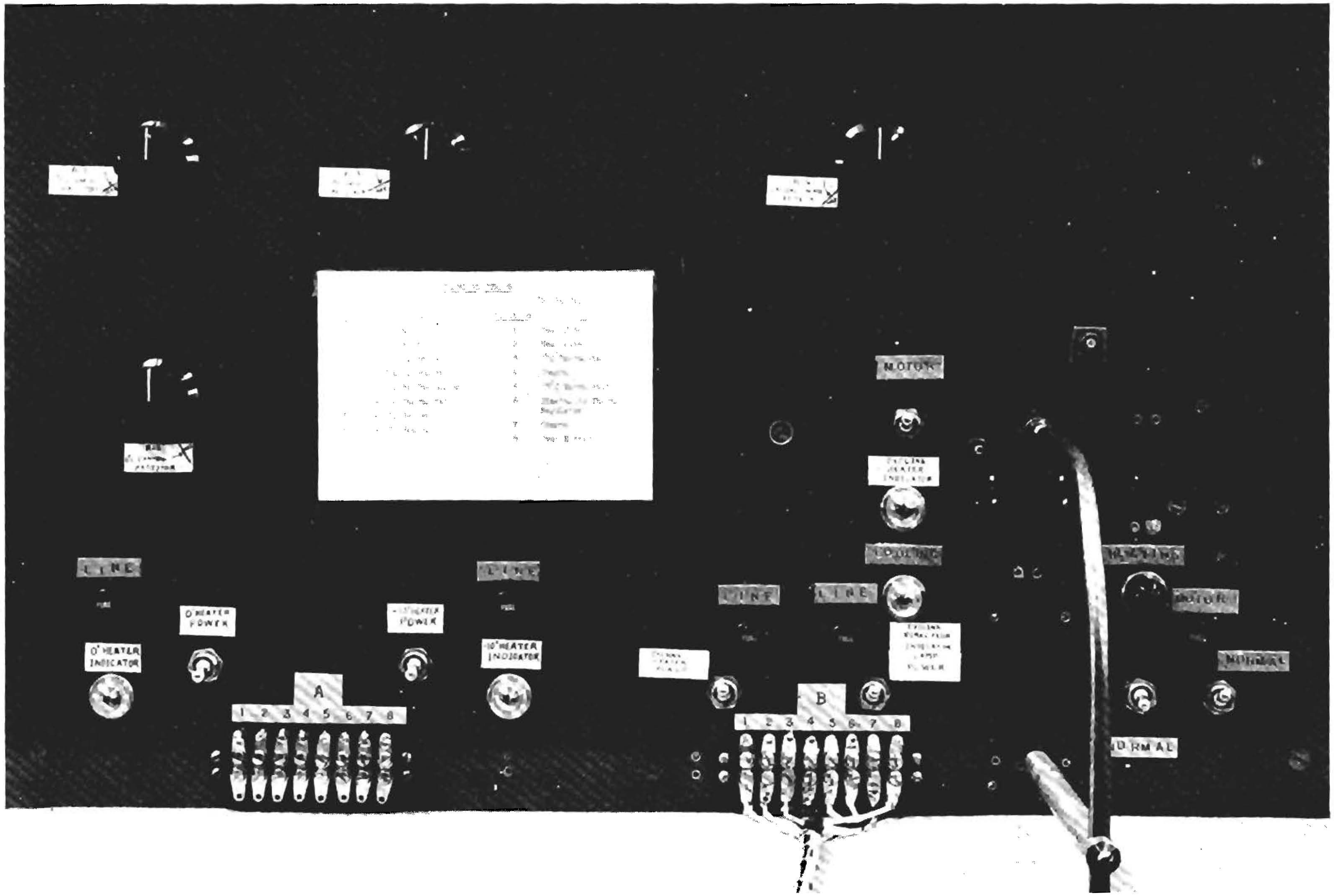


Figure 35. Control Panel for the Temperature Cycling Oven (0° to 55°C).

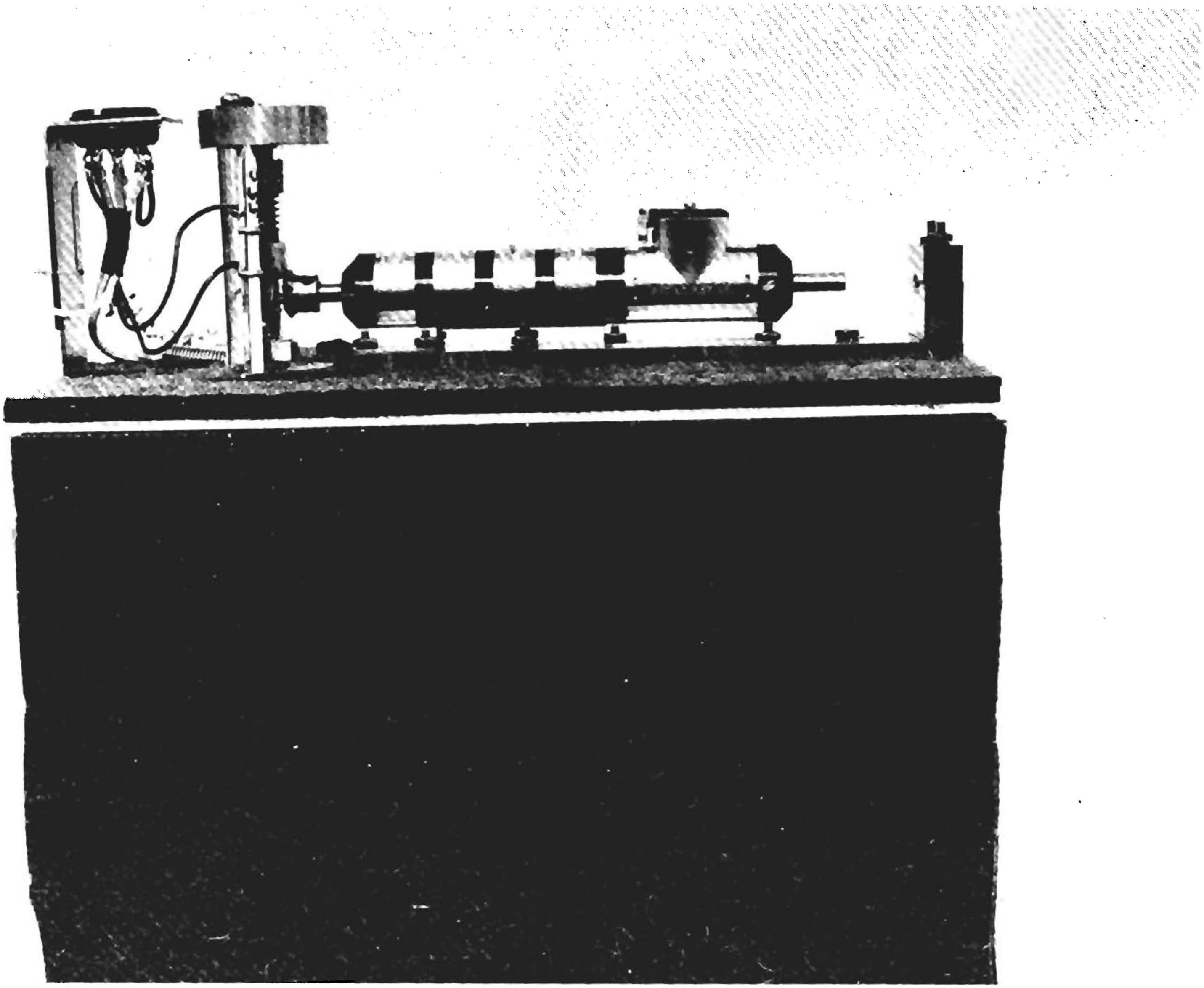


Figure 36. Temperature Cycling Oven Thermostat Drive and Speed Reducing on Top.

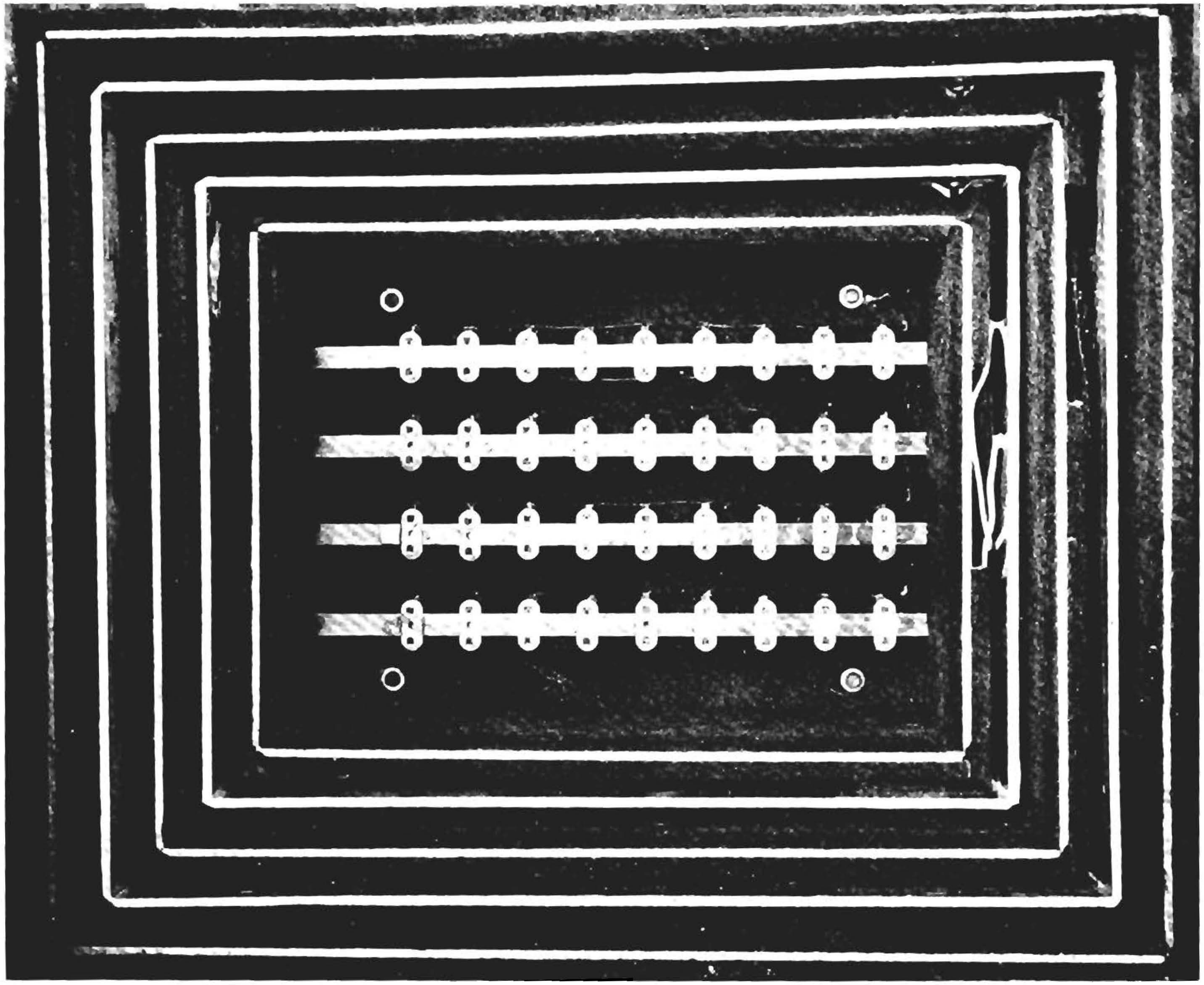


Figure 37. Interior of 55°C Constant-Temperature Oven.

that for the 200 position oven described in the Final Report of Contract DA-36-039 SC-78910.

3. Experimental Work

The primary effort during the quarter was applied to the development of the apparatus for storing the 100 mc/sec resonators at known temperatures and measuring resonator frequencies. This work has been described in Section III-2 preceeding.

Concurrently with the apparatus development some measurements were continued on the industrially fabricated resonators obtained under Contract No. DA-36-039 SC-78910. After all resonators had operated 120 to 180 days, they were removed and tested for leaks. In addition 43 resonators were fabricated here and examined for aging when stored at 85°C.

a. Leak Test. Leak Tests on approximately 200 resonators have been previously reported. The balance of the resonators were removed from the storage ovens and examined for leaks by the vacuum oil leak test. A summary of the tests on 569 resonators is shown in Table III.

It will be noted that the total of resonators indicated as leaking by the vacuum oil leak test was 472 resonators, i.e., 83 percent; approximately 14 percent had large leaks in them, and 17 percent were non leakers.

The resonators stored at 125° exhibited a higher percentage of leakers than the average, especially a higher ratio of units with large leaks to those with small leaks.

The correlation between the frequency behavior of the resonators and the leak size indicated was not especially good. However, those with large leaks or several small leaks usually had relatively rapid drift rates, whereas those with very small or no leaks indicated usually give lower drift rates. A part of the resonators with the larger drift rates observed with increased

TABLE III

NUMBER OF LEAKERS FOUND IN INDUSTRIALLY FABRICATED RESONATORS BY THE VACUUM OIL LEAK TEST

Group No.	Number Tested	Resonators Stored at Room Temperature, 25°C: Number Leakers: Small	Large	Total	Without Leaks
1	42	39	2	41	1
2	42	24	3	27	15
3	41	27	5	32	9
4	39	20	6	26	13
5	42	27	7	34	8
6	24	21	0	21	3
Totals	230	158	23	181	49
Percentage of Total	100%	68.5%	10%	78.5%	21.5%

Group No.	Number Tested	Resonators Stored at 85°C: Number Leakers: Small	Large	Total	Without Leaks
1	33	29	0	29	4
2	33	29	2	31	2
3	33	26	2	28	5
4	33	19	5	24	9
5	32	20	6	26	6
6	32	27	4	31	1
Totals	196	150	19	169	27
Percentage of Total	100%	76.5%	9.7%	86.2%	13.8%

Group No.	Number Tested	Resonators Stored at 125°C: Number Leakers: Small	Large	Total	Without Leaks
1	24	16	3	19	5
2	24	20	0	20	4
3	24	8	11	19	5
4	23	9	10	19	4

(Continued)

TABLE III (Continued)

Group No.	Number Tested	Resonators Stored at 125°C: Number Leakers Small	Large	Total	Without Leaks
5	24	13	9	22	2
6	24	21	2	23	1
Totals	143	87	35	122	21
Percentage of Total	100%	60.5%	24.5%	85.3%	14.7%
GRAND TOTALS					
25°	230	158	23	181	49
85°	196	150	19	169	27
125°	143	87	35	122	21
Totals	569	395	77	472	97
Percentages of Totals	100%	69.5%	13.6%	83%	17%

temperature may be due to accelerated corrosion of a bimetallic electrode of nickel and silver in the presence of water vapor. It is apparent that the vacuum oil leak test did indicate some small leaks which did not exist prior to the test and that certain other aging parameters existed that could partially mask aging effects due to leaking. These evidences of small leaks, however, are conjectured to give evidence of probable susceptibility to leaking. Leak determination by helium leak-detector methods gave even poorer correlation with resonator aging, and many units were indicated as non leakers that were shown to be obvious leakers by the vacuum oil leak test. Hence the vacuum oil leak test is a more sensitive test than the helium leak test or any other leak test currently being used in the industry; its major fault is that it may indicate very small leaks which do not exist at atmospheric pressure.

Occasional intermittent leaks have been observed and some can-coating agents may give temporary seals until exposed to a pressure reduction on the exterior of the can. This leads to the possibility that vacuum impregnation of micro-pores in the can may be accomplished with a suitable plastic or liquid sealant. The completed resonator would be immersed in the material in liquid condition, pumped to a pressure of a fraction of a millimeter of mercury and gas readmitted to the chamber; the resonator would then be removed from the liquid and allowed to dry. This treatment should seal many of the fine pores now causing trouble. A better base design, as previously pointed out, would also diminish the number of probable leakers.

b. Resonators Fabricated and Measured. Forty-three 16.25 mc/sec resonators were fabricated, placed in storage at 85°C and measured for frequency periodically. These were as follows:

Identification	Plating	Number Fabricated and Measured	Comments
X-1 - X-6	Al only	6	Same as Group T, Bakeout 1 hr.
Y-1 - Y-9	Al only	9	Bakeout 2 hrs. No Overcoat
Z-1 - Z-8	Al + Au	8	Au Overcoat
7-1 - 7-10	Al + Ag	10	Ag Overcoat
8-1 - 8-10	Al + Au	10	Au Overcoat

In periods of 45 or more days units of Groups X and Y have shown excellent stability; units of Group Z have behaved non uniformly, some good and some erratic. In a period a little over 30 days, units of Group 7 have shown fairly good stability; units of Group 8 have been measured only over a few days.

Typical behavior patterns of better units of Groups X, Y, Z, and 7 are shown in Figures 10, 11, 12, and 13 respectively. Measurements of Groups X and Y have supported the trend previously measured for aluminum plated units of Groups N, and T, except that R_s values of Group X were high. The reason for the high R_s has not been determined but appears to be associated with loading of the unit during sealing the glass base to the envelope. Bakeout removes much of the loading and reduces R_s. The processing of Y has indicated that the bake-out time of 3 hours may be reduced at least to 2 hours without perceptibly damaging the frequency stabilities or R_s values of the aluminum plated resonators.

The measurements on the bimetal plating of Al + Ag have indicated that this combination may not be as poor as had been indicated originally by work here, i.e., the processes of diffusion and moment of inertia change may not occur readily through the oxide barrier between the aluminum and silver. On the other hand, in the presence of small leaks, corrosion of aluminum may certainly be enhanced by contact with the silver.

The gold plated units behaved erratically, i.e., some exhibited good stability and others poor. The trends will be clearer after the units of Group No. 8 have been measured for a period of 60 days.

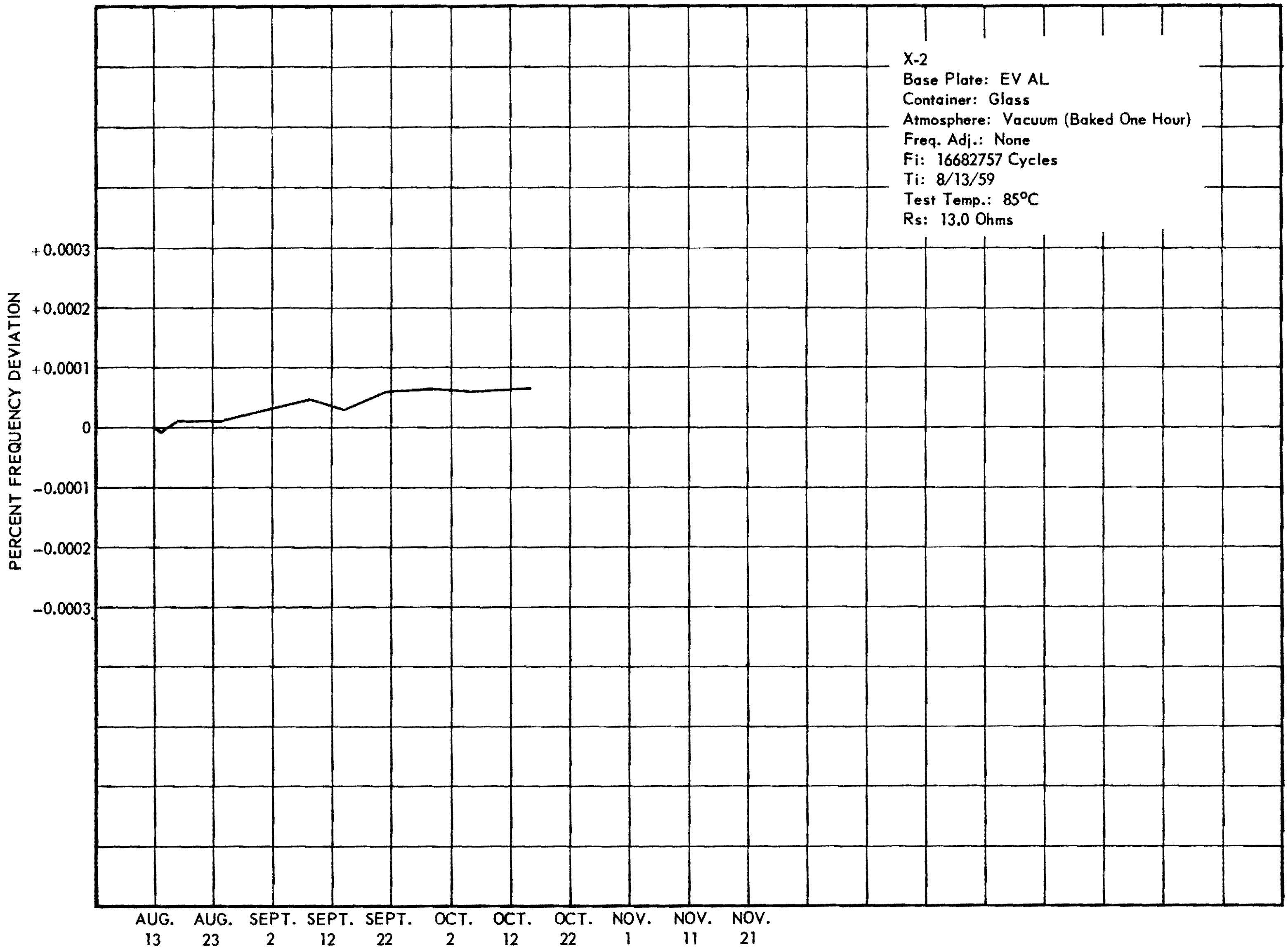


Figure 38. Frequency Drift of Resonator X-2; Al Platting, 1 Hr. Vacuum Bakeout.

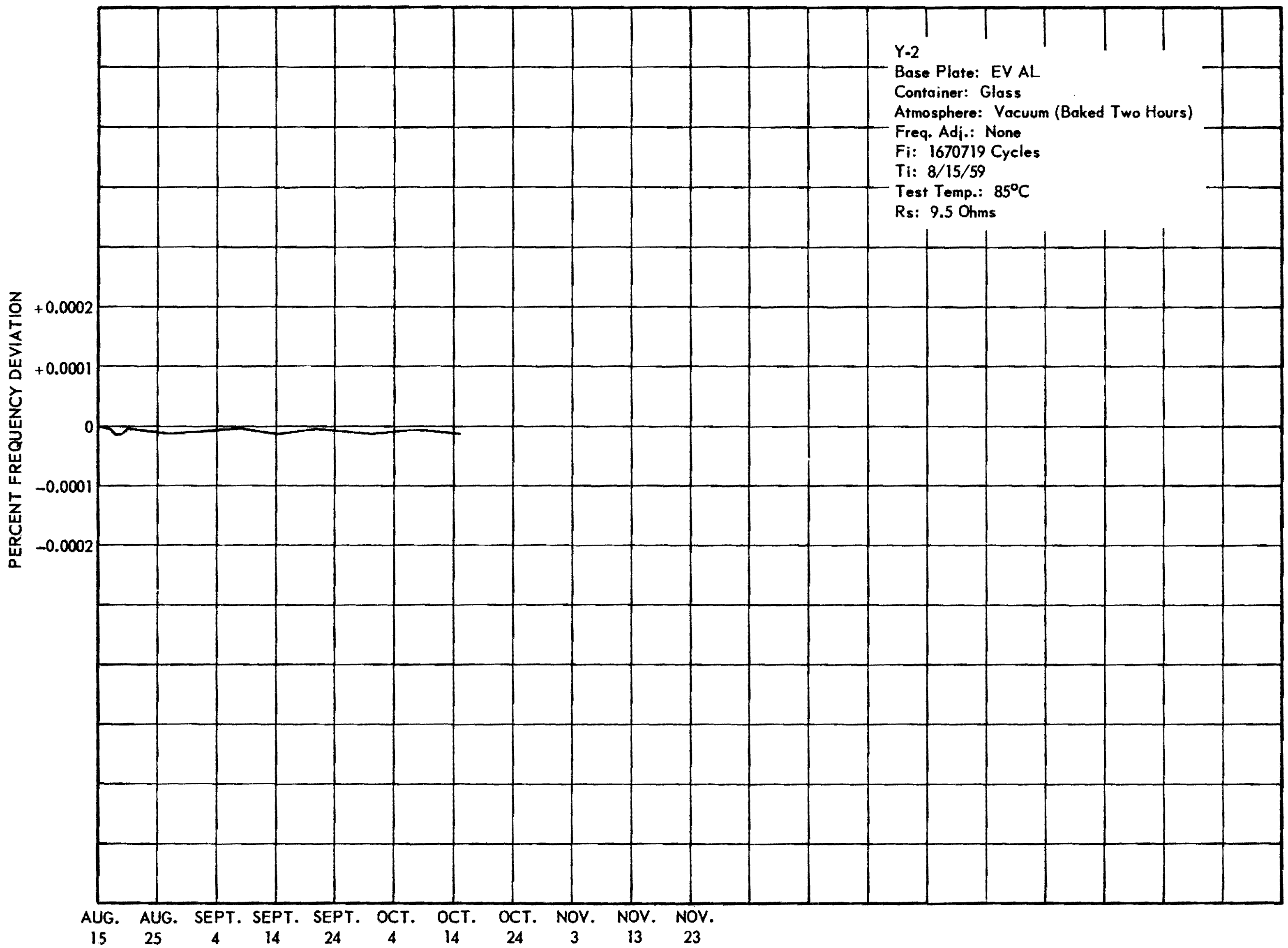


Figure 39. Frequency Drift of Resonator Y-2; Al Plating, 2 Hr. Vacuum Bakeout.

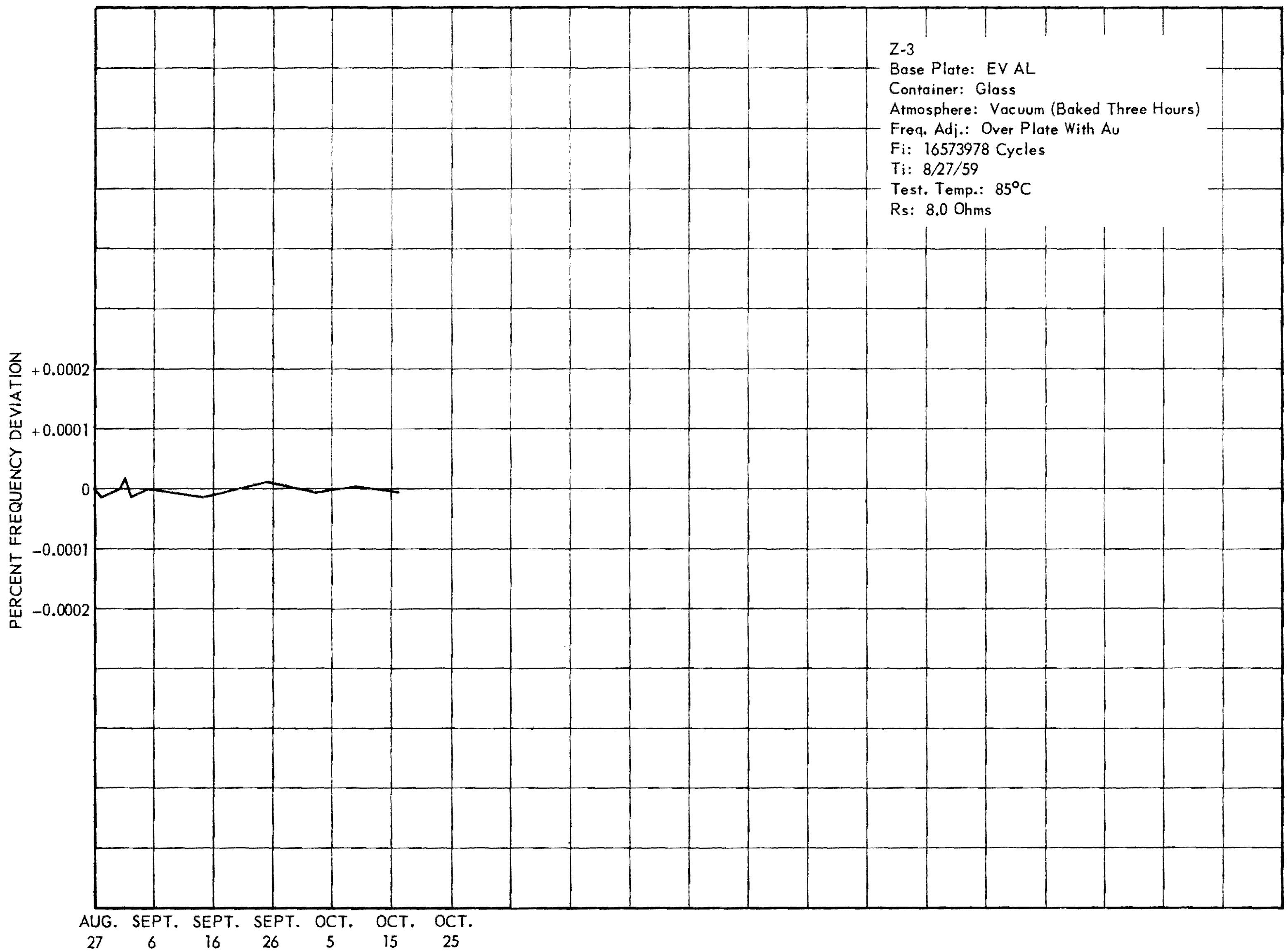


Figure 40. Frequency Drift of Resonator Z-3; Al + Au.

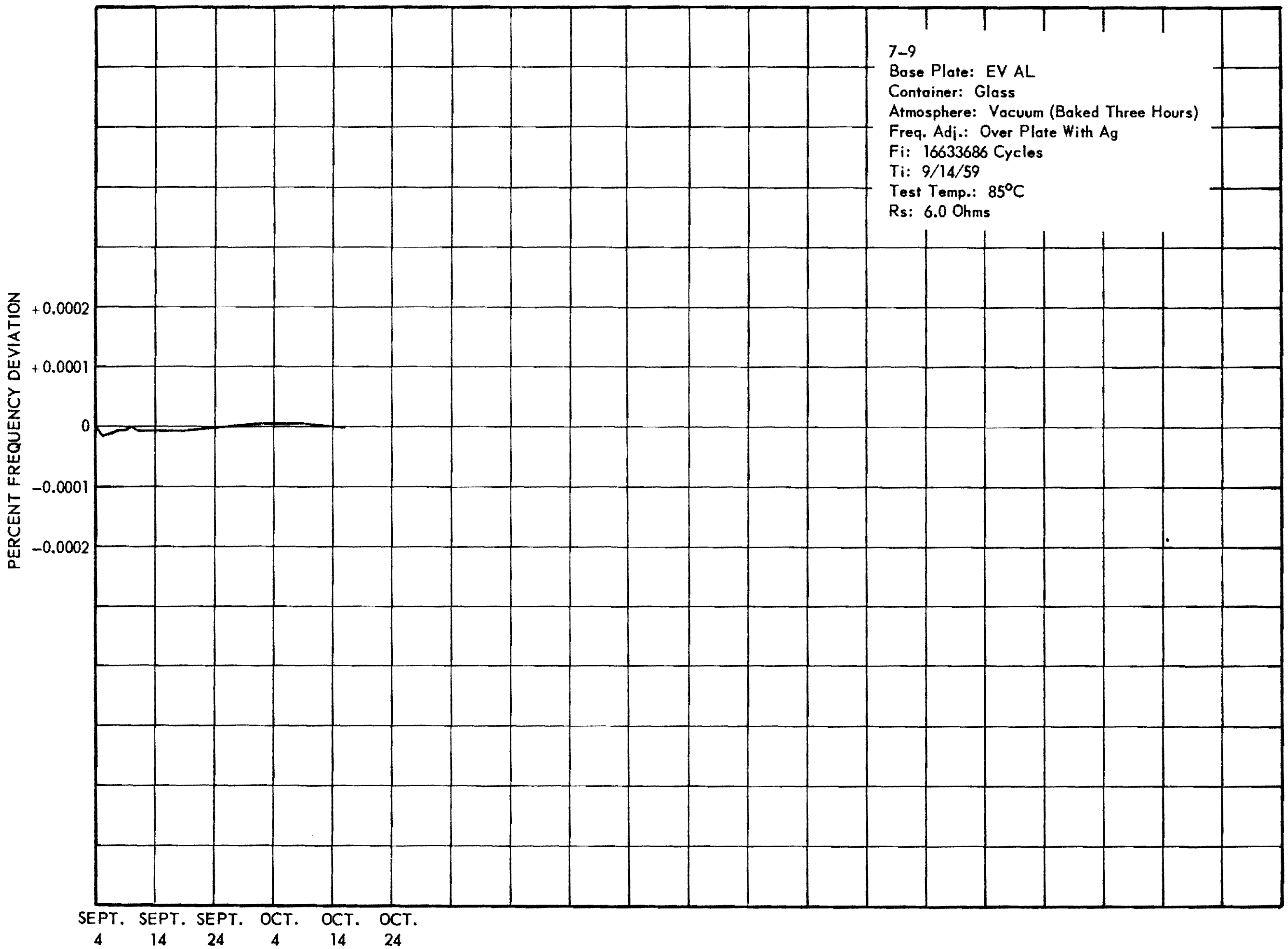


Figure 41. Frequency Drift of Resonator 7-9; Al + Ag.

V. CONCLUSIONS

Under Phase I, studies of the spectra and polarization patterns of beveled circular crystals and of triangular crystals have indicated that the analysis of either of these crystals would be considerably more complicated than that of the rectangular crystals.

The mode chart preparation for both the strong and weak responses of the rectangular crystals is progressing rapidly. Dimensional reductions of about 10 microns per step have been found sufficiently small for tracing many of the weaker responses.

The mode chart preparation has not progressed sufficiently to permit a correlation with the theories of vibration of rectangular crystals.

Under Phase II, the accuracy of the substitution measurement system is within the limits specified for a practical crystal test set in the PURPOSE of this report. Several of the commercial instruments which are presently employed in the system must be replaced by specially designed units. For example, the signal cource and the display (voltmeter or oscilloscope) should be included as integral parts of the test set.

Initial tests of the Marconi Signal Generator stabilization system indicate that the unit can be stabilized sufficiently to satisfy the present requirements for crystal measurements.

Under Phase III, equipment for storage and measurement of 100 mc resonators at 55°C and for cycling through the temperature range 0° to 55°C periodically has been completed. An oven for storage of units at 0°C has been largely completed.

Resonator blanks are on hand for fabrication of 100 mc units operated at the 5th, 7th, and 9th overtones.

Studies of resonators of 16.25 mc plated with aluminum have continued to exhibit high stabilities with drifts less than two ppm per year. Bakeout times at 180°C before final sealing may feasibly be reduced from three to two hours.

Aluminum plated resonators coated with bimetal films of Al + Ag or Al + Au have exhibited stabilities better than anticipated. This behavior indicates that some drifts previously observed and ascribed to diffusion of one metal into the other may be caused by enhanced corrosion rate of the aluminum film, in contact with a more noble metal and in the presence of a very small leak in the container. Further tests, however, will be required to prove either hypothesis.

VI. PROGRAM FOR THE NEXT INTERVAL

Mr. Tsuzuki will continue the preparation of the mode charts for the rectangular crystals. Approximately six months will be required to complete this work.

The polarization studies which were started at the end of this report period will also be continued as an aid in tracing and identifying the modes of vibration as observed on the mode charts.

Tests of the crystal substitution measurement system will continue under Phase II. The practicability of adapting this system as a unitized crystal test set will be studied.

The construction of the final units of the Marconi frequency stabilization system will be completed.

During the next quarter studies of the aging of 16.25 mc resonators plated with aluminum, or with aluminum and a second metal, will be continued in an effort to establish a preferred method of overcoating these resonators to frequency.

Limited studies of 100 mc resonators stored at 55°C will be undertaken.

VII. IDENTIFICATION OF KEY TECHNICAL PERSONNEL

The major portion of the experimental program under Phase I, during this period, was conducted by Mr. Yasuo Tsuzuki. Mr. Tsuzuki received his B.S. in Electrical Engineering from the Yokahama National University in 1955 and his M.S. in Electrical Engineering from the Tokyo Institute of Technology in 1957. He studied under Dr. Koga during his stay at the Tokyo Institute of Technology. He served as Teaching Assistant and Instructor in Electrical Engineering at the Yokahama National University from 1957 until his employment at Georgia Tech. During this time, he was active in quartz crystal research including field tests of single sideband applications of crystals. Mr. Tsuzuki was employed by this project for a period of one year beginning in August 1959.

During this period, Mr. Witt has assumed the duties of Assistant Project Director of Phase I in charge of local research activities and report preparation in the absence of Dr. Koga. Dr. Koga has retained the responsibilities of over-all guidance.

The personnel time on Phase I for the contract period 1 July 1959 through 30 September 1959 is as follows:

NAME	TITLE	HOURS
H. Fukuyo	Research Engineer	322
I. Koga	Project Director Special Research Scientist	202
J. E. Rhodes, Jr.	Senior Research Engineer	120
Y. Tsuzuki	Assistant Research Engineer	367
S. N. Witt, Jr.	Assistant Project Director Research Engineer	20

No personnel changes have occurred under Phase II during this period. The personnel time for the period 1 July 1959 through 30 September 1959 is as follows:

NAME	NAME	HOURS
S. N. Witt, Jr.	Project Director Research Engineer	480
V. K. Woodcox	Research Assistant	480

No personnel changes have occurred under Phase III during this period. The personnel time for the period 1 July 1959 through 30 September 1959 is as follows:

NAME	NAME	HOURS
R. B. Belser	Project Director Research Associate	84
M. D. Carithers	Technician	152
W. D. Dawson	Student Assistant	172
J. J. Erasmus	Assistant Research Engineer	344
W. H. Hicklin	Assistant Research Engineer	608
J. C. Meaders	Research Assistant	556

Respectfully submitted:

Samuel N. Witt, Jr.
Assistant Project Director
for Issac Koga, Project
Director, Phase I

Samuel N. Witt, Jr.
Project Director, Phase II

Approved:

Arthur L. Bennett, Chief
Physical Sciences Division

Richard B. Belser
Project Director, Phase III

Report No. 2 (Quarterly), Projects No. A-402-11, -12, and -13

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5	ATTN: SIGFM/EL-PFP
5	ATTN: SIGFM/EL-PFT
32	ATTN: SIGFM/EL-PF, Mr. G. Goldenberg

REPORT NO. 3 (QUARTERLY)

PROJECTS NO. A-402-11, -12, and -13

QUARTZ CRYSTAL STUDIES AND MEASUREMENTS

PHASE I. MOTIONAL PARAMETERS

By

ISSAC KOGA, YASUO TSUZUKI, and S. N. WITT, JR.

PHASE II. EQUIVALENT ELECTRICAL PARAMETERS

By

S. N. WITT, JR. and V. K. WOODCOX

PHASE III. AGING OF QUARTZ RESONATORS

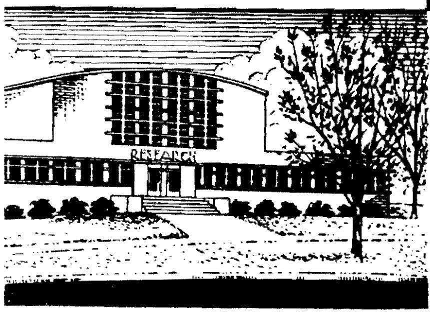
By

R. B. BELSER and W. H. HICKLIN

CONTRACT NO. DA-36-039 SC-78905

1 OCTOBER 1959 TO 31 DECEMBER 1959

PLACED BY THE U. S. ARMY
SIGNAL RESEARCH AND DEVELOPMENT LABORATORIES
FORT MONMOUTH, NEW JERSEY



Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia

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QUARTZ CRYSTAL STUDIES AND MEASUREMENTS. PHASE I: MOTIONAL PARAMETERS, Issac Koga, Yasuo Tsuzuki, and S. N. Witt, Jr., PHASE II: EQUIVALENT ELECTRICAL PARAMETERS, S. N. Witt, Jr. and V. K. Woodcox, PHASE III: AGING OF QUARTZ RESONATORS, R. B. Belser and W. H. Hicklin.

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ENGINEERING EXPERIMENT STATION
of the Georgia Institute of Technology
Atlanta, Georgia

REPORT NO. 3 (QUARTERLY)

PROJECTS NO. A-402-11, -12, and -13

QUARTZ CRYSTAL STUDIES AND MEASUREMENTS

PHASE I. MOTIONAL PARAMETERS

By

ISSAC KOGA, YASUO TSUZUKI, and S. N. WITT, Jr.

PHASE II. EQUIVALENT ELECTRICAL PARAMETERS

By

S. N. WITT, JR. and V. K. WOODCOX

PHASE III. AGING OF QUARTZ RESONATORS

By

R. B. BELSER and W. H. HICKLIN

CONTRACT NO. DA-36-039 SC-78905

1 OCTOBER 1959 TO 31 DECEMBER 1959

The object of this research is the enhancement of the understanding of the behavior of quartz crystals as frequency control and filter devices.

PLACED BY THE U. S. ARMY
SIGNAL RESEARCH AND DEVELOPMENT LABORATORIES
FORT MONMOUTH, NEW JERSEY

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I. PURPOSE

The purpose of this contract is to advance the state of the art of applications of quartz crystals as frequency control and filter elements. Investigations and studies are conducted simultaneously in three areas of specialization:

Phase I. Motional Parameters

Phase II. Equivalent Electrical Parameters

Phase III. Aging of Quartz Resonators

Phase I is concerned with the study of motional parameters of thickness-shear and contour-shear modes of vibration of crystal plates. The purpose of Phase I is fourfold:

1. To continue the measurements of frequency and strain distributions of thin circular discs;

2. To measure frequency and strain distributions of plates having a smaller diameter-thickness ratio and adequately bevelled to eliminate couplings with other modes;

3. To measure frequency and strain distributions of some triangular plates of the AT-cut; and

4. To conduct investigations which are concerned with the measurement of parameters of the equivalent electric circuit of circular plates, particularly to determine the influence of the electrode diameter and the motional capacitance constant, Γ, on the motional parameters.

Phase II is concerned with methods and techniques for determining the equivalent electrical parameters of quartz crystal units. The purpose of Phase II is threefold:

1. To continue the investigation of applications of crystal units in VHF and UHF oscillators for frequencies above 175 mc/sec to determine the following:

   (a) crystal parameters useful in oscillator circuit design,

   (b) methods and techniques for determining crystal parameters, and

   (c) test requirements for crystal units;

2. To design and construct experimental models of 175- to 300-mc/sec quartz crystal test sets capable of:

   (a) testing crystal units employing HC-6/U and HC-18/U holders,

   (b) determining the series resonant condition with a frequency accuracy of ±1 ppm,

   (c) indicating directly the crystal power dissipation with an accuracy such that the resultant frequency accuracy is ±1 ppm, and

   (d) operation with crystal power dissipation in the range 0.2 to 4.0 mw;

3. To perform studies and investigations leading to the development of methods and techniques for determining the equivalent parameters of crystal units in the frequency range of 300 to 500 mc/sec with emphasis on information pertinent to the eventual development of crystal specifications and crystal test sets.

Phase III is concerned with the effects of processing techniques and materials on aging of quartz crystal units. The purpose is threefold:

1. To fabricate experimental crystal units as follows:

   (a) AT-cut, fundamental mode, 16.0 mc/sec, gold and silver base plate, adjusted to frequency by evaporation or electrolysis of a second compatible metallic film, evacuated glass holders,

(b) AT-cut, third and fifth overtone modes, 48.0 and 80.0 mc/sec, evaporated aluminum base plate only, evacuated glass holders, and

(c) AT-cut, third and fifth overtone modes, 48.0 and 80.0 mc/sec, evaporated aluminum base plate, adjusted to frequency with evaporated aluminum, evacuated glass holders;

2. To measure for 6 months the frequency and resistance of crystal units stored at approximately 25°, 85°, and 125°C;

3. To determine, from an analysis of the data, the degree of compatibility of the frequency adjustment metal with the base plate metal.

In addition to the above requirements any other problems pertinent to the three phases which may arise during the course of the studies and which are mutually agreed upon between the contracting officer's technical representative and the contractor will be investigated.

II. ABSTRACT

Under Phase I, the spectra studies of crystal D-1 have continued. Polarization studies, which were initiated at the beginning of this period, were made for all dimensional reductions. These combined studies have made possible the identification of most of the stronger modes of crystal vibration. Identification of additional modes is anticipated as the x_o dimension of the crystal is further reduced.

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III. PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

No publications, lectures, or reports other than as required by the contract have resulted from work under this contract during this report period.

On 24 November, Dr. G. K. Guttwein and Dr. R. Bechmann visited Georgia Tech. Progress on Phases I and III was reviewed. A decision to make spectra and polarization measurements on special 3-mc/sec crystals up to 28 mm in size was reached. The purpose of this addition to the program of Phase I is to investigate the behavior of circular electrodes of diameters from 3 to 21 mm.

IV. FACTUAL DATA

A. Phase I. Motional Parameters

1. Introduction

This phase of the work, assigned the Project No. A-402-11 by the Engineering Experiment Station of the Georgia Institute of Technology, was initiated on 1 March 1959 and is a continuation of the work prior to that date on Contract No. DA-36-039 SC-78910, Project No. A-402-1. This report, for the period from 1 October 1959 to 31 December 1959, represents a continuation of the work described in the Interim Report and Report No. 2 (Quarterly) for the preceding periods of the current contract.

As previously reported, some elementary measurements were made on beveled circular and triangular crystal plates. These measurements were discontinued because of the complexity of the vibrational modes.

A set of 16 rectangular crystal plates were prepared for detailed study. Two of these plates (D-1 and D-2) were selected for initial studies because of their similarity. Both high and low resolution spectra were obtained for crystal D-1 for x_o dimensions from the initial 24.56 to 24.20 mm in 45 steps during the previous report period. No polarization studies were made; however, several vibrational modes were tentativly identified but were not reported, pending verification.

During the current report period, the x_o dimension of crystal D-1 was further reduced to 23.754 mm for a total of 112 steps to date. A total of 16 vibrational modes have been identified. Polarization patterns were obtained at all x_o dimensions during this period.

2. Third Overtone Spectra of Rectangular Crystal Plates

Spectra measurements for crystal D-1 as a function of the x_o dimension have continued. During this report period, the x_o dimension of this crystal was reduced from 24.2 to 23.754 mm in 67 steps averaging 6 microns per step.

Figure 1 is the mode chart of weaker responses of crystal D-1. Figure 2 is the mode chart of the stronger responses. The equipment used to obtain these data was described in Report No. 2 (Quarterly). No changes were made in the equipment except for a slight readjustment in the bias level of the 12AU7 detector tube of Figure 9 of Report No. 2 (Quarterly).

A calibration of the spectra measurement equipment was obtained by substituting various resistors for the test crystal and noting the amplitude of the response of the photographic recorder. The calibration curve is shown in Figure 3 for the crystal connected across the entire coil, B, (see Figure 9 of Report No. 2 (Quarterly)). This connection is normally used when making spectra measurements. The calibration curve was obtained after the slight readjustment of the detector bias referred to above. Such calibration is capable of giving only an approximate indication of the motional resistance of the test crystal.

3. Polarization Studies

Equipment for making polarization studies was placed in operation at the beginning of this report period. A block diagram of this equipment was shown as Figure 16 of Report No. 2 (Quarterly). The gain of the amplifier-detector is broad band but not adjustable; thus, amplitude scaling of the polarization pattern is accomplished by varying the output of the signal generator. Neither the crystal drive voltage nor the crystal power is held constant as the equipment is adjusted for different responses; however, the signal generator attenuator dial setting is recorded for each measurement run.

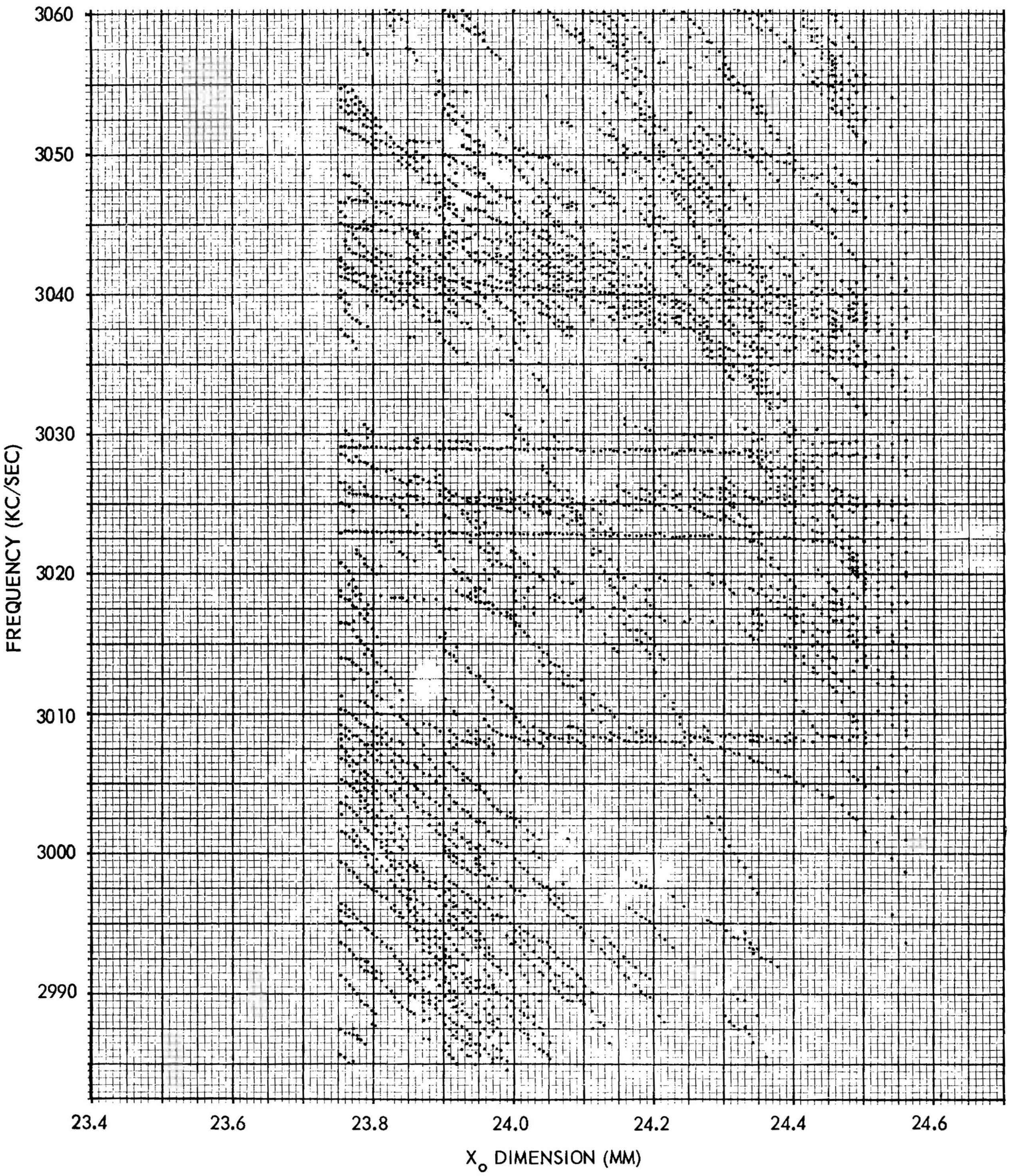


Figure 1. Mode Chart of Weaker Responses of Crystal D-1.

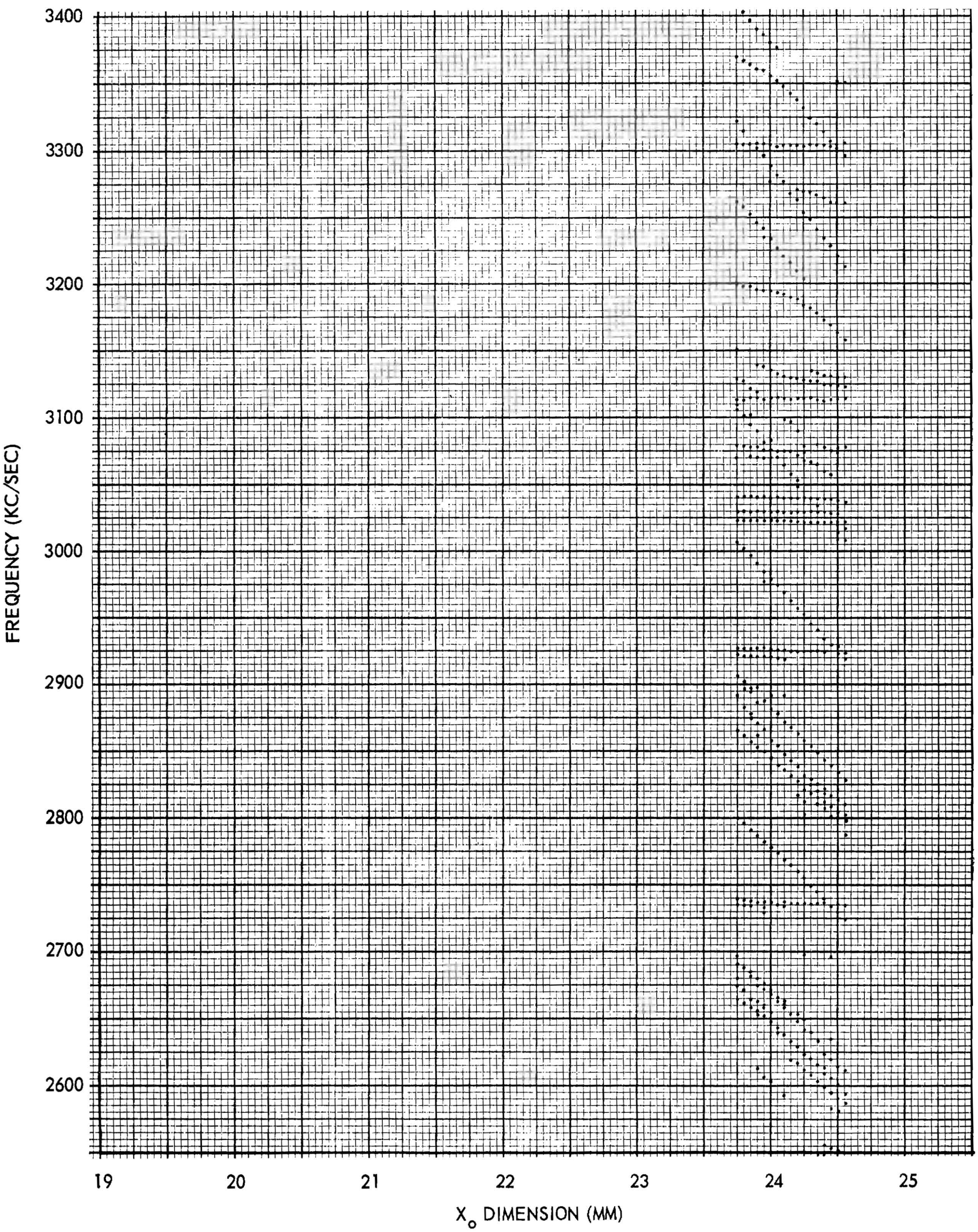


Figure 2. Mode Chart of Stronger Responses of Crystal D-1.

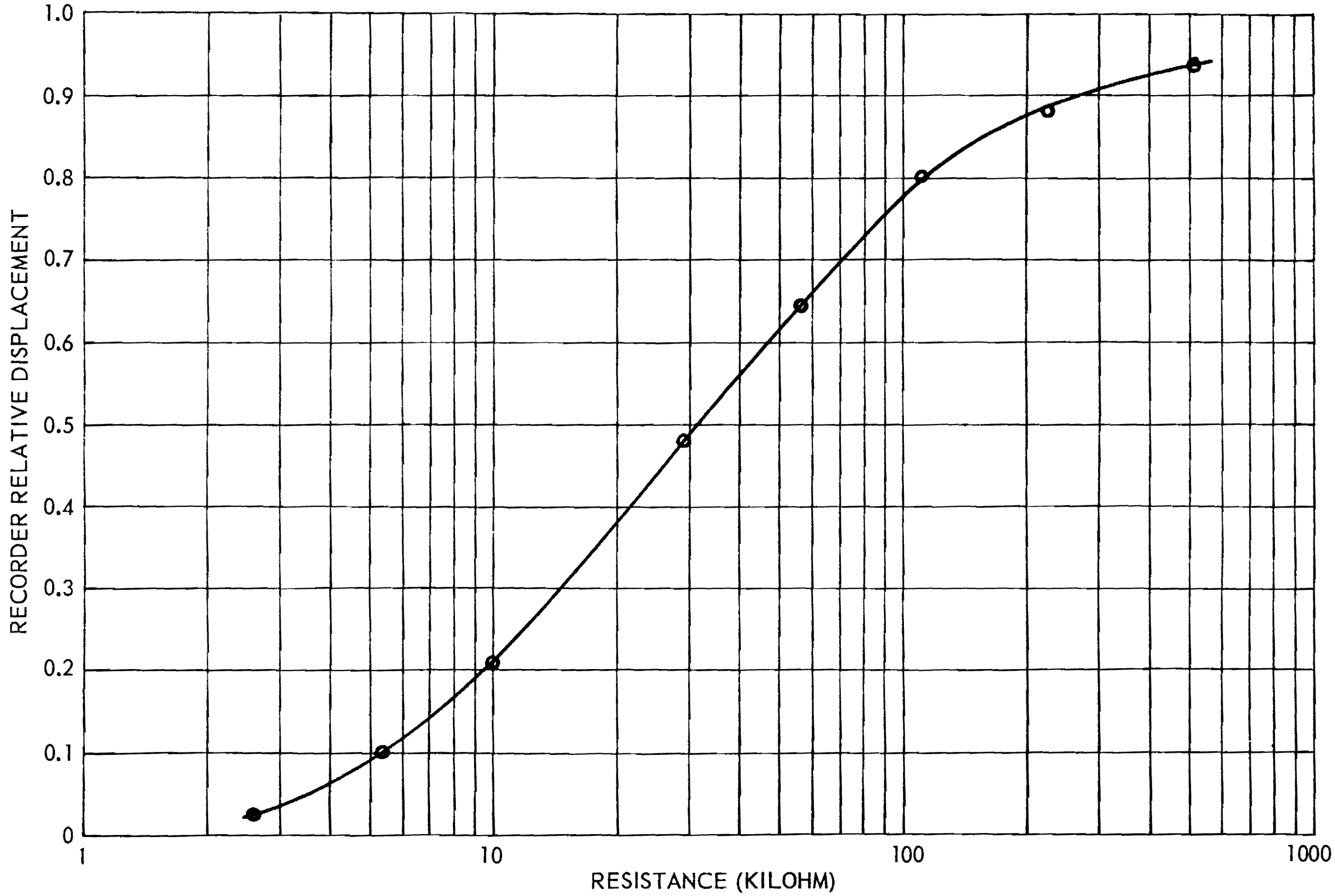


Figure 3. Motional Resistance Calibration Curve for the Spectra Measurement Equipment.

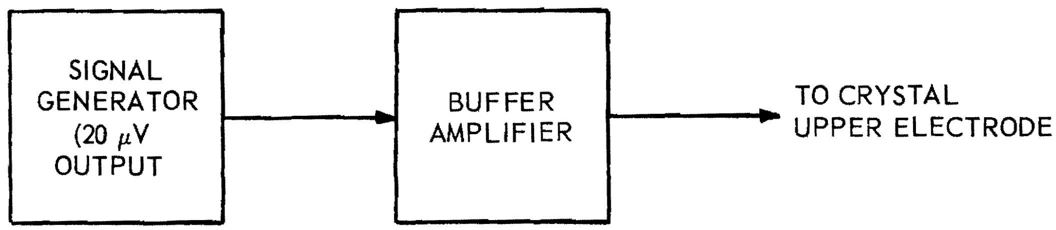
The frequency response and output impedance of the buffer amplifier are shown in Figure 4. Since the approximate motional resistance of the crystal can be determined from the spectrum and Figure 3, the crystal drive during a polarization run can be estimated from the signal generator attenuator dial setting and the curves of Figure 4. The maximum available drive power with the present equipment is less than 65 μw.

The amplitude characteristics of the amplifier-detector-recorder system are shown in Figure 5. From these curves, in combination with the estimated crystal drive, the relative degree of crystal polarization can be estimated at the various responses.

Polarization patterns for crystal D-1 were measured for each of the stronger responses (until each response was definitely identified) for each dimensional reduction of the crystal. Each response was detected by the polarization measurement equipment rather than setting the frequency from the spectrum data. Many relatively strong polarization responses which appeared weak on the spectra were thus located. Correlation between the polarization response and the spectrum response was obtained by measuring the frequency of the polarization response with a BC-221 Frequency Meter. For closely spaced responses, the accuracy of this Frequency Meter was insufficient. A Berkeley Model 5570 Frequency Meter will be used for future measurements.

4. Interpretation of Data

Careful interpretation of the spectra and polarization records has permitted the identification of many of the crystal vibrational modes. Figure 6 is a copy of Figure 2 with the mode identifications shown. The spectra are most useful in tracing the frequency variations of the modes and thus often indicate



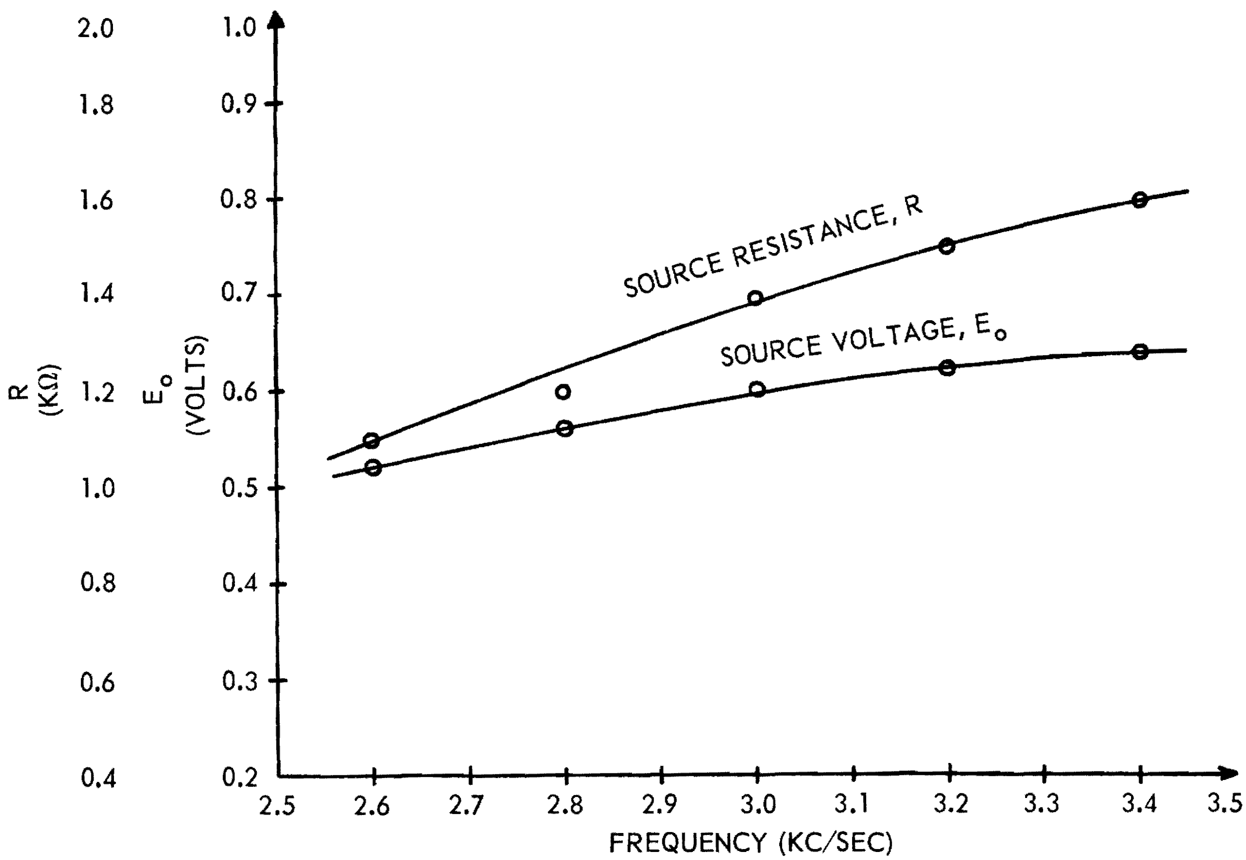


Figure 4. Source Voltage and Source Impedance Characteristics of the Buffer Amplifier.

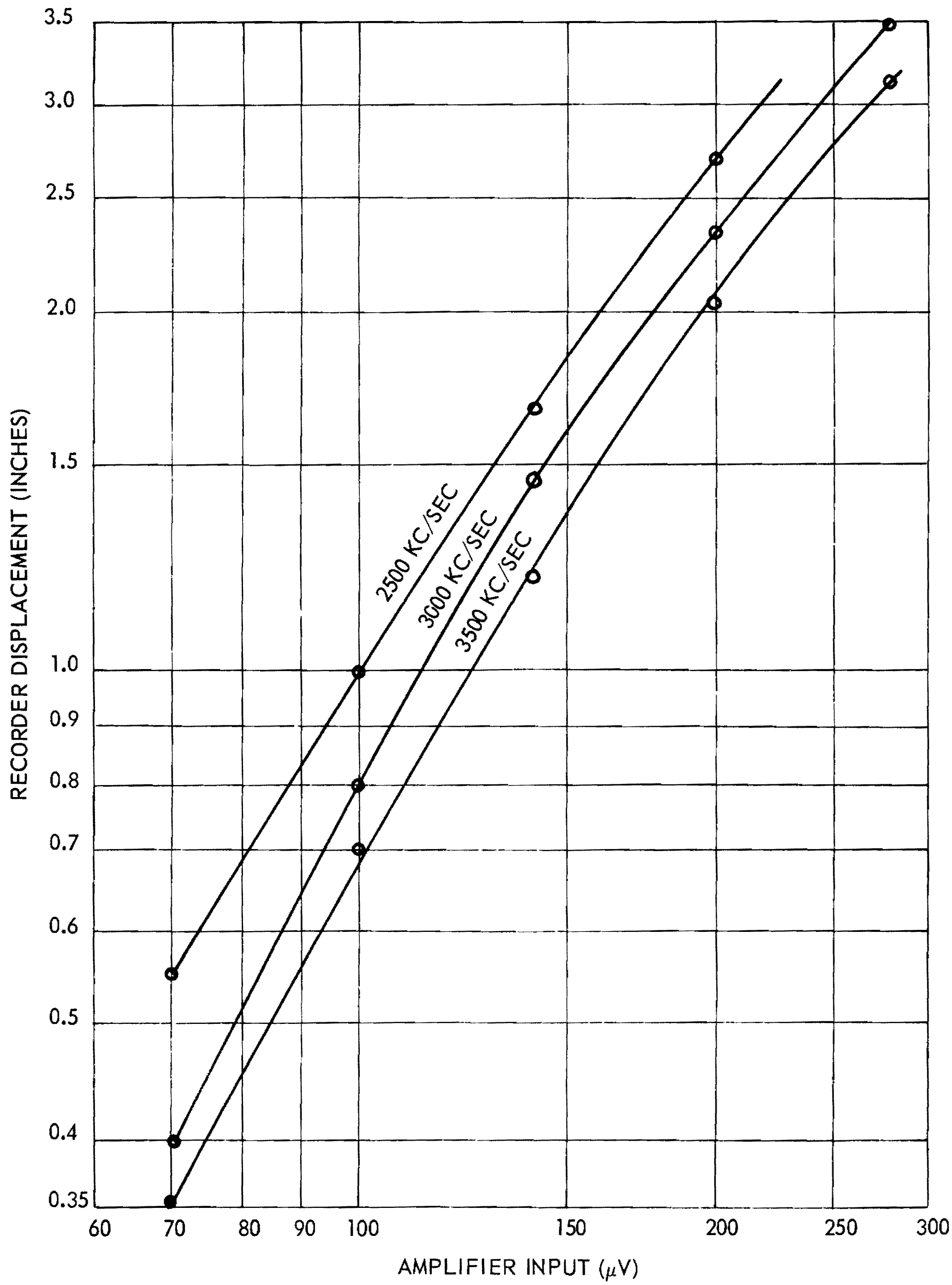


Figure 5. Amplitude Characteristics of the Amplifier-Detector-Recorder System.

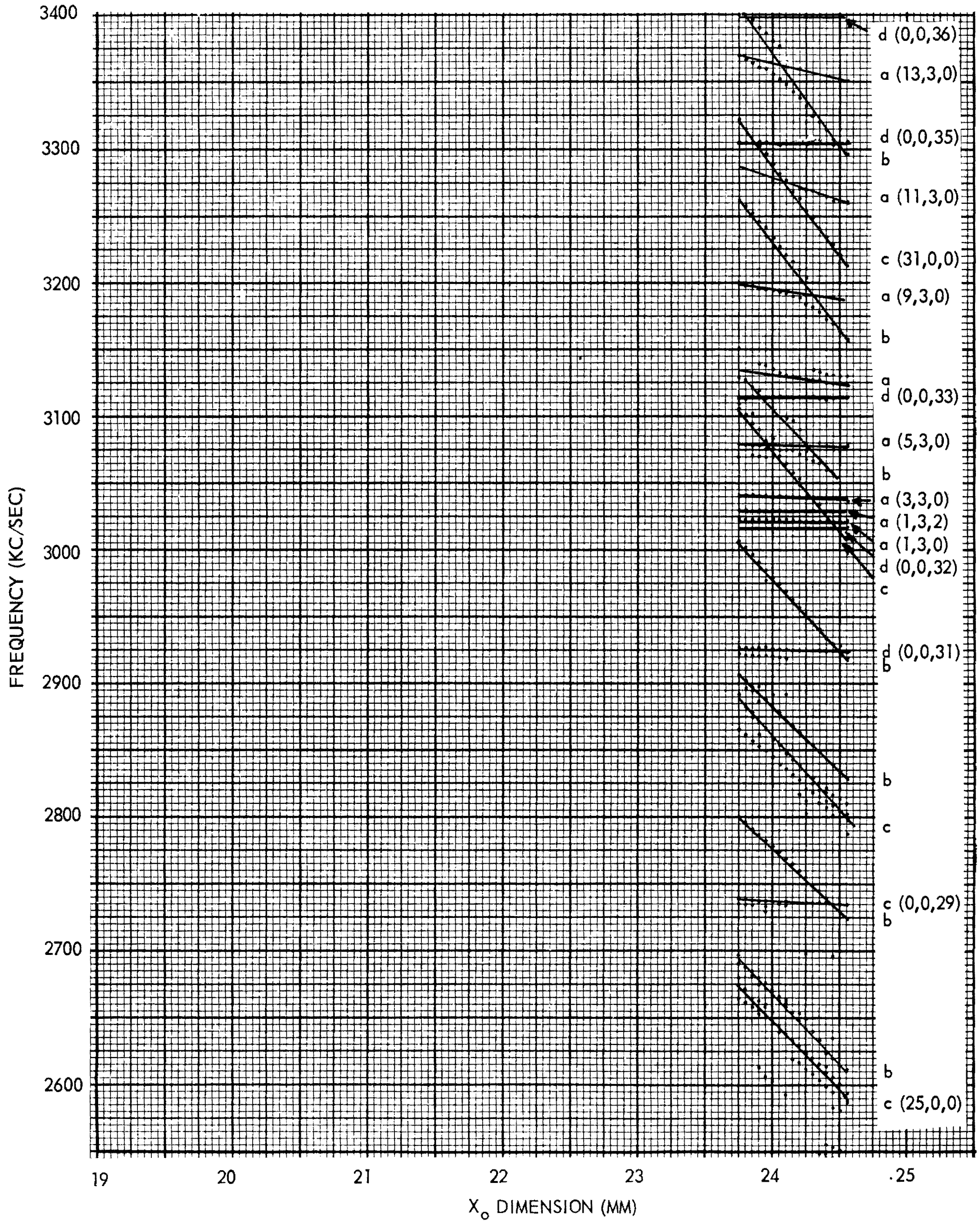


Figure 6. Mode Identifications of the Stronger Responses of Crystal D-1.

the type of vibration as defined in Quarterly Report No. 1, Contract No. DA-36-039 SC-78910. Modes of three of the four types described in this reference have been identified.

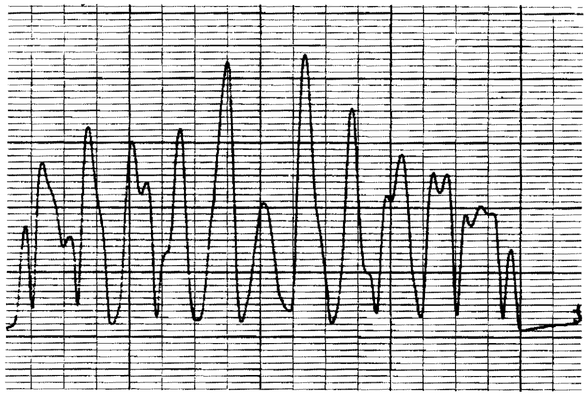
The exact nature of the vibrational mode can sometimes be tentatively identified by observing the frequency spacing between evenly spaced modes having identical slopes on the mode chart. Further verification results from comparing this information with the physical dimensions of the crystal. However, conclusive identification can be made only by studying the polarization patterns. The number of loops and nodes can be counted in both the x_o and z_o directions (polarization patterns were obtained in both directions for each response). Typical polarization patterns indicating this procedure are shown in Figure 7. Descriptions of these patterns together with a listing of the identified modes within each type follow:

(1) Type a vibrations identified were (1,3,0), (3,3,0), (5,3,0), (9,3,0), (11,3,0), (13,3,0), (15,3,0), and (1,3,2). A typical polarization pattern for the type a mode in the x_o direction of order (11,3,0) is shown in Figure 7(a).

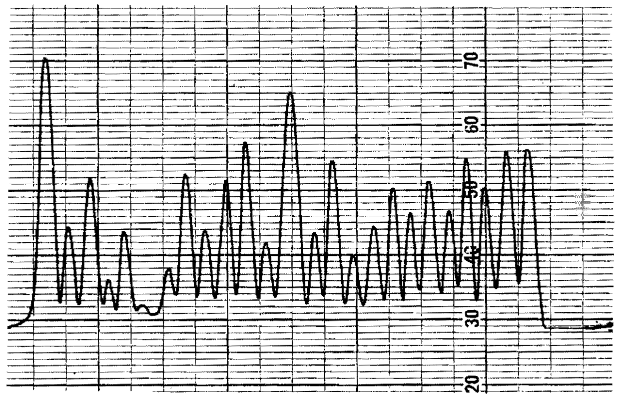
(2) Type c vibrations identified were (25,0,0) and (31,0,0). Figure 7(b) is an example of the (25,0,0) order in the x_o direction.

(3) Type d modes of two types, even and odd, were identified. The odd modes were (0,0,29), (0,0,31), (0,0,33), and (0,0,35). The even modes were (0,0,32) and (0,0,36). Figures 7(c) and 7(d) are examples respectively, of the odd and even modes of orders (0,0,33) and (0,0,32) in the z_o directions.

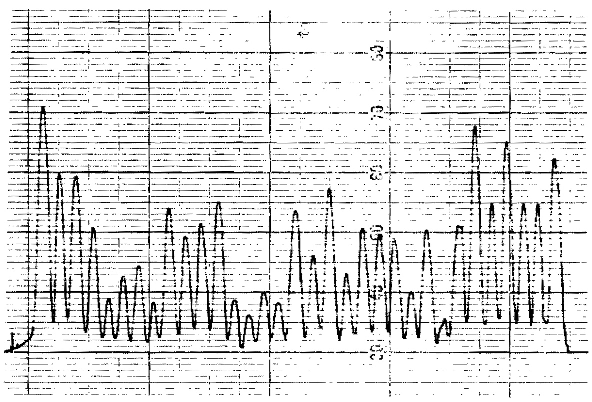
Most of the modes described above were easily located on the spectra recordings, as may be seen from Figure 6. In some regions, certain modes were



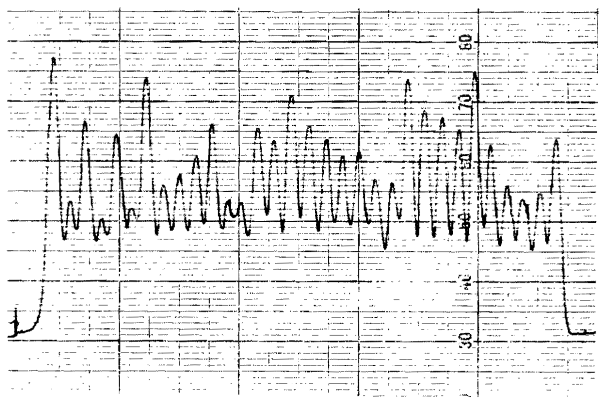
(a) TYPE a VIBRATION OF ORDER (11, 3, 0)



(b) TYPE c VIBRATION OF ORDER (25, 0, 0)



(c) TYPE d VIBRATION OF ORDER (0, 0, 33)



(d) TYPE d VIBRATION OF ORDER (0, 0, 32)

Figure 7. Typical Polarization Patterns for Crystal D-1.

more difficult to trace because of mutual coupling between modes. Examples are the type a modes of orders (13,3,0) and (9,3,0). The two even order type d modes could generally not be located, even as very weak responses, on the spectra recordings; however, because of their relatively large charge distributions, they were readily located by the polarization measurements. Other even order type d modes can probably be located as the x_o dimension of the crystal is reduced to where mutual coupling is absent in the appropriate regions of the frequency spectrum.

As the various modes were definitely identified, the polarization studies were discontinued at the respective frequencies except for occasional verification checks, and the amount of time required to obtain the polarization data was thus reduced.

B. Phase II. Equivalent Electrical Parameters

1. Introduction

This phase of the work, assigned the Project No. A-402-12 by the Engineering Experiment Station of the Georgia Institute of Technology, was initiated on 1 March 1959 and is a continuation of the work prior to that date on Contract No. DA-36-039 SC-78910, Project No. A-402-2. This report, for the period from 1 October 1959 to 31 December 1959, represents a continuation of the work described in the Interim Report and in Report No. 2 (Quarterly) for the preceding periods of the current contract.

A substitution system for measuring the parameters of quartz crystals at high frequencies was described in the previous reports under this contract. A comparison between substitution measurements and Crystal Measurements Standard measurements showed a maximum disagreement of less than 4 percent for resistance and less than 0.0002 percent for frequency. The procedure for determining crystal Q was discussed in Report No. 2 (Quarterly). This procedure was applied during the current period to 12 crystal overtone responses.

A frequency stabilization system for the Marconi Signal Generator was also described in Report No. 2 (Quarterly). At that time, a complete breadboard model of the system had been constructed and tested. Both long- and short-term frequency variations of the Signal Generator were greatly reduced by the system. During the current period, a more refined model of the system was constructed and tested.

2. The Substitution Measurement System

a. Crystal Mount Modifications. The substitution measurement system was described in the Interim Report and in Report No. 2 (Quarterly). During the current period, the crystal diode (visible in Figure 22A of the Interim Report) of the crystal mount was found to be defective because of stress resulting from repeated insertion of crystals and resistors. The body of this diode was in contact with the crystal at one point when the crystal was properly positioned in the mount. When the defective diode was replaced, a different mounting procedure was employed. The diode was recessed further into the mount, as may be seen in Figure 8, so that no contact could be made with the crystal unit.

The characteristics of the new diode were essentially the same as those of the original unit. Much of the original data were rerun to verify this.

b. Measurement Procedures. The procedure for making a substitution crystal measurement was originally described on pp. 40 and 42 of the Interim Report. The step-by-step procedure has since been modified in some respects

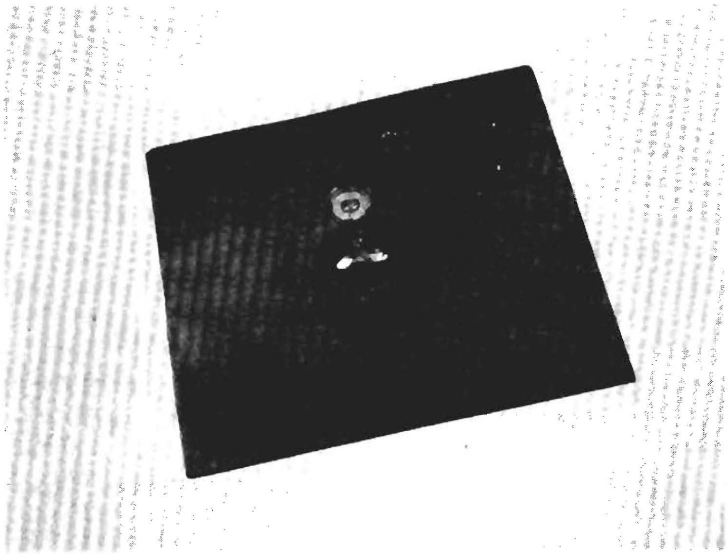


Figure 8. Crystal Mount for the Substitution Measurement System.

and is, therefore, revised as follows:

Step 1. Set the equipment for sweep operation and locate the overtone response by tuning the Signal Generator frequency.

Step 2. Adjust the susceptance stub for a maximum value of point A of Figure 9 (point A is the minimum point on the curve regardless of the shape of the curve).

Step 3. Gradually reduce the sweep deviation while readjusting the frequency to maintain point A at the center of the sweep.

Step 4. When zero deviation is reached, observe the d-c microvoltmeter (which may be continuously connected across the mount diode along with the oscilloscope) and alternately adjust the frequency for a minimum voltage and the susceptance stub for a maximum voltage.

Step 5. Record the resulting voltage, frequency (f_r), and stub setting.

Step 6. Replace the crystal with a substitution resistor and adjust the stub for a maximum voltage.

Step 7. Repeat step 6 with other substitution resistors (employing linear interpolation, if necessary) until a maximum voltage equal to that observed in step 4 is obtained and record the calibrated resistance (or conductance) value as R_{min} (or G_{max}).

Step 8. Repeat the above seven steps using section B of Figure 9 and adjusting frequency in step 4 for a maximum rather than a minimum. (The only required permanent data point is given in step 7 as the resistance which is recorded as R_{max}, or the conductance, which is recorded as G_{min}.)

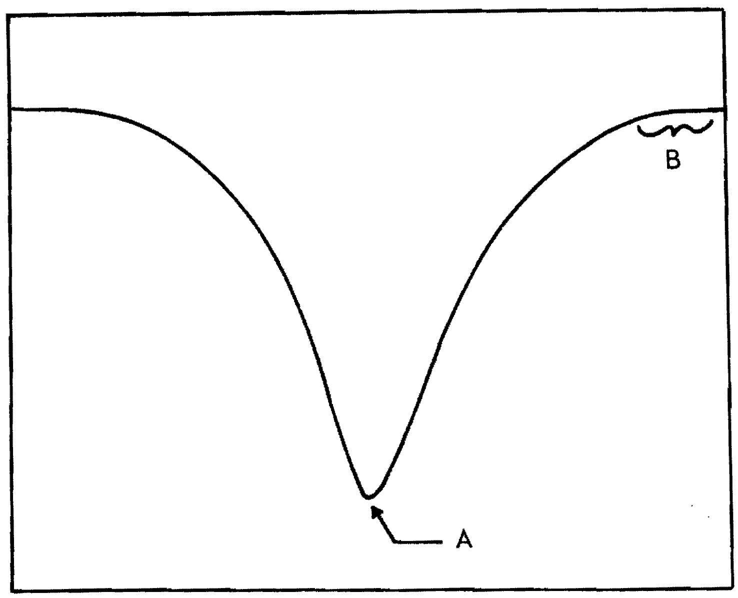


Figure 9. Ideal Sweep Characteristic with the Substitution Measurement System.

Information about the quality of a crystal response can be obtained while steps 1 and 2 are being performed by observing the oscillographic patterns of the crystal responses. Typical responses are shown in Figure 10. Figure 10(a) shows a relatively-spurious-free, low-resistance, high-Q response. Figure 10(b) is a response which is equally spurious-free but which has higher resistance and thus lower Q. Poorer accuracy may be expected in determining the value of Q for this response due to the gradual slope of the sides of the response. Figure 10(c) shows a low resistance but highly distorted response. The distortion is produced by the lossy crystal holder as was described for a theoretical crystal in the Final Report of Contract No. DA-36-039 SC-78910. At higher frequency responses, the distortion would become more severe. At frequencies near the holder resonant frequency, the response would be essentially the inverse of Figure 10(a) or 10(b). Figure 10(d) shows a crystal response with a spurious response occurring very near the main response. Calculation of Q by the substitution method is very difficult for a response of this type. Figure 10(e) shows a crystal with spurious response of lower resistance than the main response. The separation between the two responses is adequate; however, the usefulness of such a crystal would be questionable. Figure 10(f) shows two phenomena. First, the response is inverted as mentioned above. Second, a discontinuity occurs because of excessive drive level.

Of the responses of Figure 10, only Figure 10(a) represents a completely satisfactory crystal. The substitution measurement system, however, is capable of determining G_{max} and G_{min} for any crystal response. Figure 9 shows the region where each resistance is measured for the ideal response of Figure 10(a). Where discontinuities occur, such as in Figure 10(f), the maximum and minimum resistance values are completely meaningless.

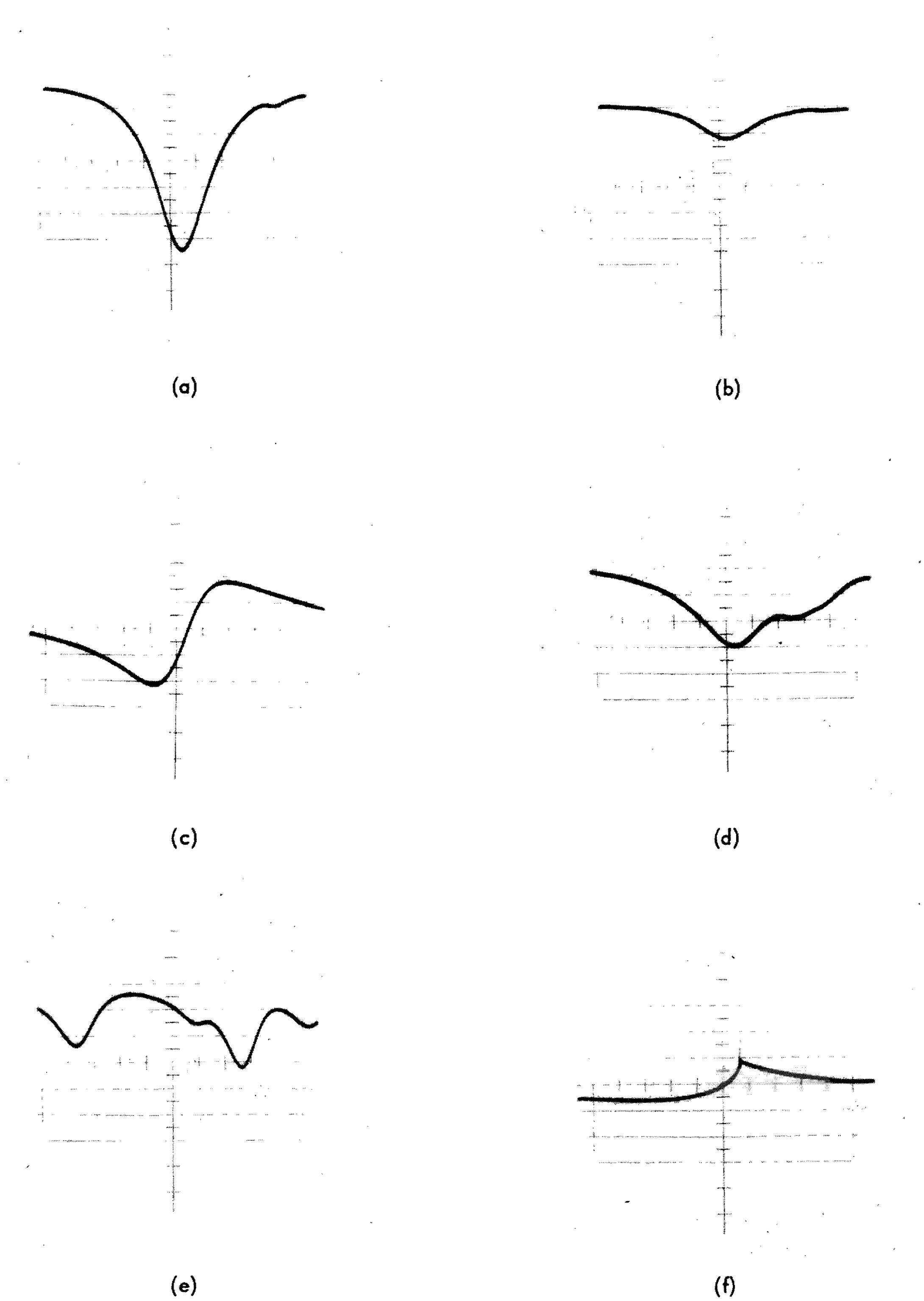


Figure 10. Typical Sweep Displays with the Substitution Measurement System.

The crystal Q may be measured, by use of the procedure to be described below, for most of the responses of Figure 10, but will be meaningful only for responses similar to that of Figure 10(a) and possibly 10(b) and 10(c). This restriction is not considered to be severe since only the response of Figure 10(a) can be used to satisfactorily control the frequency of current oscillator types.

The eight-step procedure for determining the parameters of a crystal with the substitution measurement system yields: (1) the conductance at antiresonance, G_{max}; (2) the frequency at antiresonance or at G_{max}; (3) the minimum conductance away from antiresonance, G_{min}; and (4) the antiresonating element value in terms of stub length. The only remaining important parameter is the crystal Q. A method for determining a quantity, Q', was described in Report No. 2 (Quarterly). Q' is the incremental form of the differential quotient which defined Q and is thus less than Q by a relatively constant and small percentage for the conditions specified. The necessary data for calculating Q' are obtained by continuing the measurement procedure as follows:

Step 9. Place a substitution resistor with conductance of $G_k = 0.85\ G_{max} + 0.15\ G_{min}$ in the mount, adjust the stub for minimum voltage, and record the voltage (if the exact substitution resistor is not available, linear interpolation may be used to determine this voltage).

Step 10. Reinsert the crystal and adjust the stub as outlined in step 4.

Step 11. Adjust the frequency to either side of the frequency of point A of Figure 9 until the voltage is the same as the voltage in step 9, repeat for the other side, and record the frequencies as f_1 (low side) and f_2 (high side).

Step 12. From Figure 28 of Report No. 2 (Quarterly), determine θ and then calculate

$$Q' = \frac{f_r}{2}\left(\frac{2\,\theta}{f_2 - f_1}\right).$$

c. Measurement Data and Analyses. Complete substitution measurement data were obtained for 12 crystal overtone responses between 200 and 300 mc/sec. The data are shown in Table I.

For comparison purposes, the Crystal Measurements Standard System was used to obtain data comparable to the substitution data. The Standard System is capable of providing data for the calculation of actual crystal Q; however, the calculations are very involved. Also, the comparison of Q' with Q would not separate the measurement error of the substitution system from the inherent error due to the way in which Q' is defined. Thus, the Standard System was used to determine only the values of admittance at f_r, f_1, and f_2. A half-wavelength line was used between the Admittance Meter and the crystal mount so that direct admittance readings would be obtained without the use of a digital computer. The half-wavelength line reduced the accuracy of the data slightly. The crystal drive level, as indicated by an r-f voltmeter, was kept small and approximately the same in both measurement systems.

Previous data had indicated that the substitution system could determine the resonant frequency, f_r, with approximately the same accuracy as the Standard System; however, this indication was again verified by changing the frequency slightly during the Standard System measurements to determine if a greater G_{max} could be found. For the 12 responses measured, the values remained the same. Both conductance (G_r or G_{max}) and susceptance (B_r) were recorded at the frequency f_r.

Conductances and susceptances at frequencies f_1 and f_2 were then measured (G_1 and B_1 at f_1; G_2 and B_2 at f_2). The minimum conductance, G_{min}, was not measured with the Standard System because of the time involved.

All of the data were corrected on the Admittance Meter correction charts. The resonant susceptance, B_r, was subtracted from the susceptance at each of the three frequencies to simulate antiresonating the crystal. If

$$B_1' = B_1 - B_r, \; B_2' = B_2 - B_r$$

and

$$\Delta\theta = \text{ArcTan}\,\frac{B_1'}{G_1} + \text{Arc Tan}\,\frac{-B_2'}{G_2} \; ,$$

then

$$Q' = \frac{f_r}{2}\left(\frac{\Delta\theta}{f_2 - f_1}\right) .$$

The Standard System measured and calculated data are also shown in Table I.

At some of the responses, the current data were compared with circle diagram data, which had been obtained previously, to determine the angle φ as defined in Report No. 2 (Quarterly). In each case the angle was found to be between 40 and 50 degrees, as predicted by theory.

In all cases, the error in the determination of R_{min} by substitution measurements was less than ± 4 percent with respect to the Standard System data. The disagreement in Q' was less than ± 10 percent in all except three cases. In these three cases, poorer accuracy was expected due to the poor crystal overtone responses.

d. Drive Level Effects. As was stated in the previous section, the crystal drive level was kept small and approximately the same for both measurement systems. The sensitivity of both systems permitted measurements

TABLE I

COMPARISON OF RESISTANCE AND Q' MEASUREMENTS

Crystal No.	Substitution Measurement System: Frequency (Mc/Sec) f_r	f_1	f_2	G_{max} (Millimhos)	G_{min} (Millimhos)	R_{min} (Ohms)	Q'	Crystal Measurement Standard: R_{min} (Ohms)	Q'	Error (%R)	Error (%Q')
FA-67	209.9767	209.9731	209.9807	9.1	1.0	110	10,100	109	9,600	+0.9	+5.0
MA-23	210.5832	210.5817	210.5845	5.6	1.0	179	25,300	183	23,700	-2.2	+6.6
No. 5	217.0985	217.0974	217.0994	8.3	1.0	123	33,100	123	33,200	0.0	-0.3
No. 6	217.1022	217.1007	217.1039	8.6	1.0	117	24,800	116	27,400	+0.9	-8.9
No. 12	219.9821	219.9810	219.9833	7.4	1.1	134	34,900	129	28,000	+3.9	+22.0
FA-104	230.9356	230.9340	230.9374	14.0	2.3	71.5	24,100	71.0	23,600	+0.7	+2.4
FA-115	245.1036	245.0997	245.1066	25.5	3.6	39	14,300	39	13,600	0.0	+4.8
3-W	274.5305	274.5287	274.5321	14.2	2.4	70.4	28,500	69.6	28,000	+1.2	+2.0
FA-91	279.0407	279.0386	279.0427	23.6	2.7	42.4	26,800	41.0	24,800	+3.4	+7.9
No. 5	283.8949	283.8918	283.8971	9.6	2.5	104	16,100	104	13,000	0.0	+23.7
No. 6	283.9009	283.8983	283.9032	12.1	2.8	82.7	18,400	82.0	14,800	+0.9	+24.4
FA-105	296.8921	296.8893	296.8946	23.1	6.0	43.2	18,000	41.8	17,600	+3.3	+3.0

to be made with drive levels as small as 0.01 mw. Typical measurements were made at a level of about 0.1 mw. The drive level for the substitution measurement system was estimated from predetermined r-f voltage versus d-c voltage calibrations of the crystal mount diode. The drive level for the Crystal Measurements Standard System was estimated from r-f voltage measurements at the component mount at high drive levels. The attenuator on the Marconi Signal Generator was then used to reduce the drive level by the desired amount.

Typical measurements indicated that the drive level did not appreciably affect the values obtained for G_{max} or G_{min}. To determine the frequency effects, one crystal response (FA-91 at 279 mc/sec) was examined in the Crystal Measurements Standard System at three drive levels, 0.01, 0.1 and 1.0 mw. The conductance and susceptance curves at each drive level are shown in Figure 11. A Smith Chart diagram of the same data is shown as Figure 12. The departure of points from the circle of Figure 12 is within the accuracy of the Standard System since a half-wavelength rather than a short line was used between the Admittance Meter and the component mount. As may be observed from the figures, the values of G_{max}, G_{min}, and Q' of the crystal are affected very little by the drive level variations; however, the variations in frequency are relatively much more noticeable. (Here, the relative importance of each variation is based upon the desired and obtainable measurement accuracy of each parameter. If absolute measurements could be made, the effects of drive level on frequency might well be much less, by percentage, than the effects on other quantities.)

Similar variations were observed with the substitution measurement system as a function of drive level. The frequencies at maximum conductance, f_r, are marked on Figure 11 for two drive levels.

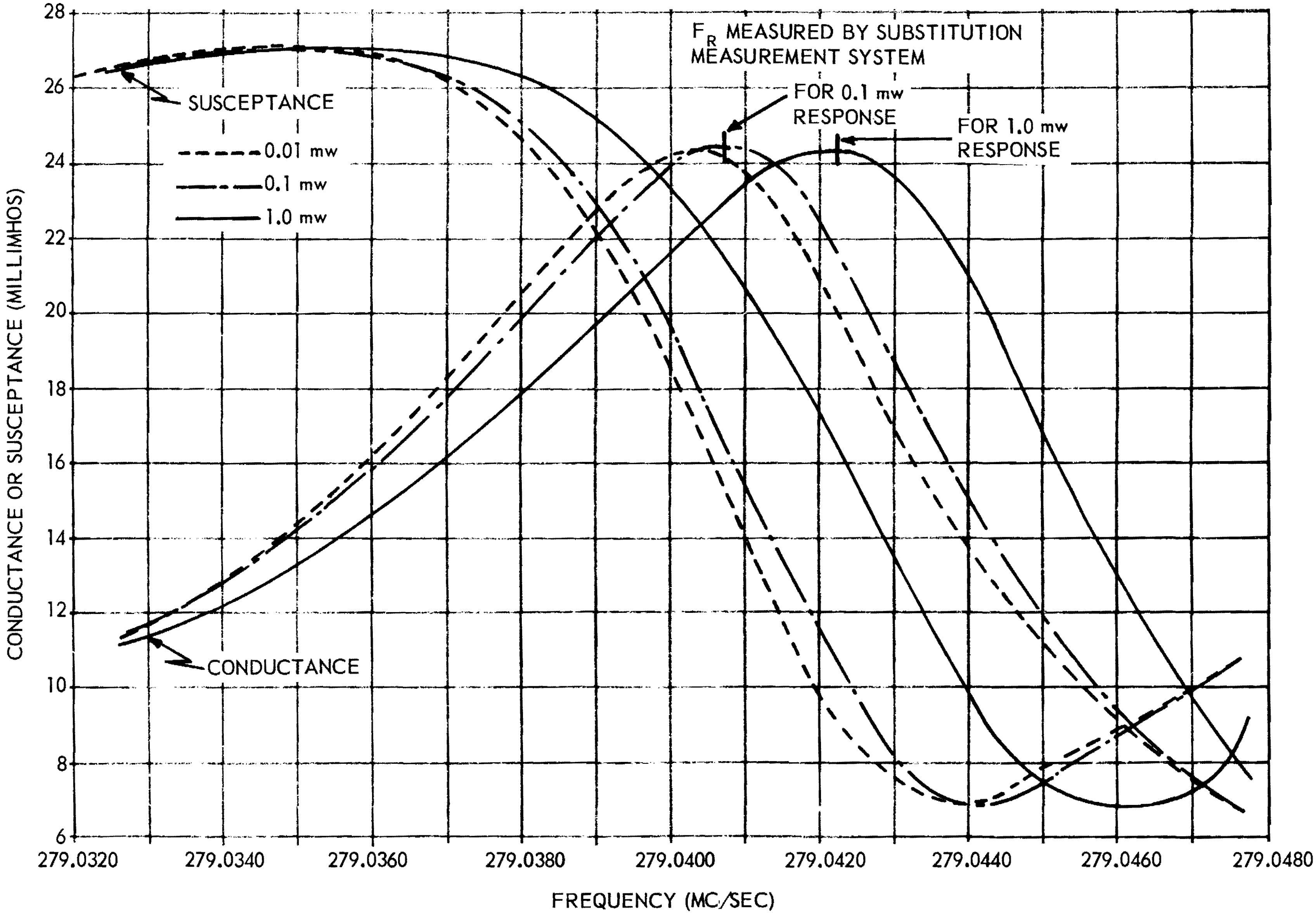


Figure 11. Effects of Drive Level on Crystal Frequency Characteristics.

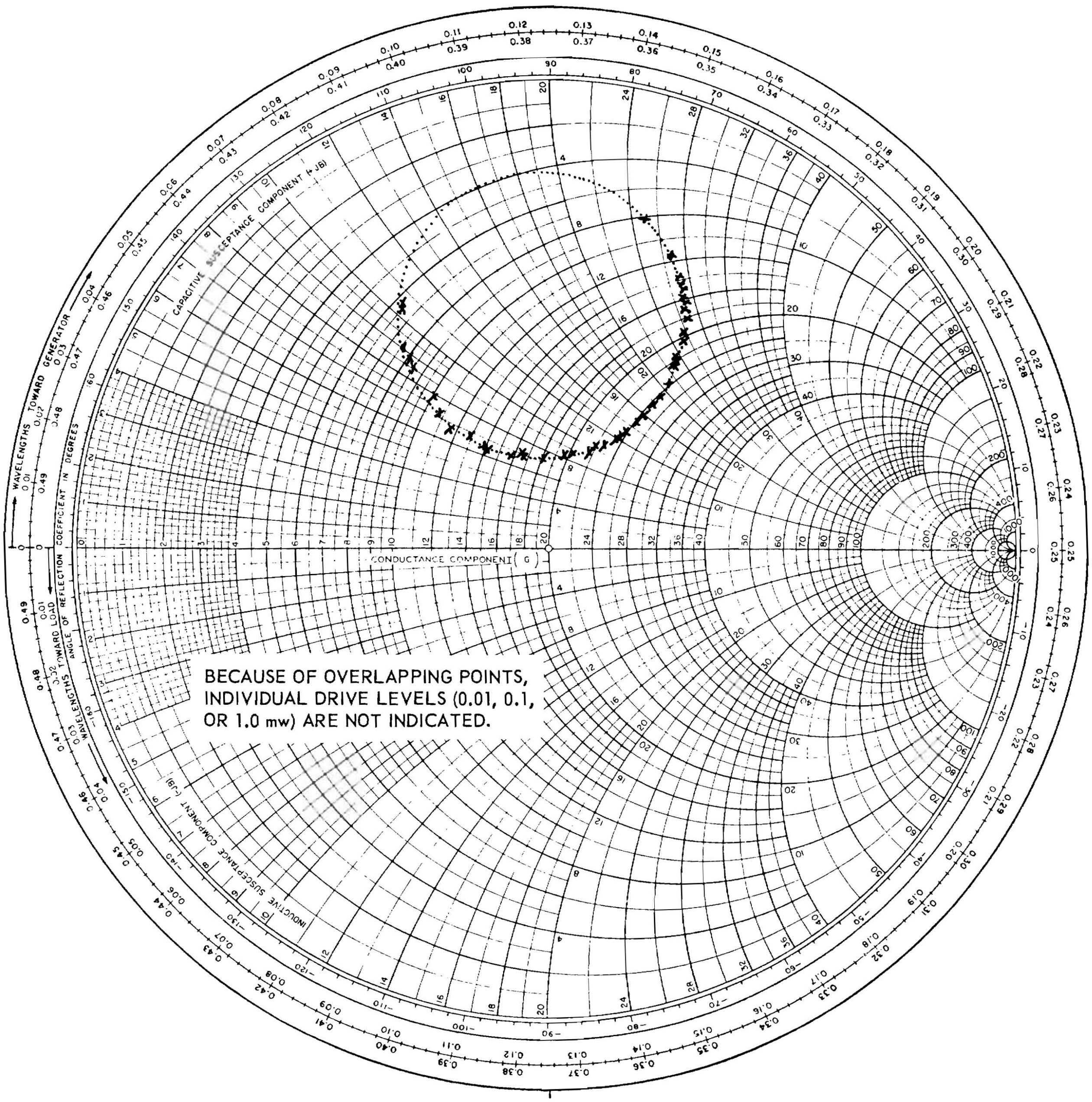


Figure 12. Effects of Drive Level on Crystal Admittance Characteristics.

To minimize the drive level effects, the measurements described in the previous section were made at drive levels of less than 0.1 mw. Drive levels were also kept approximately the same for the two measurement systems.

3. Stabilization of the Marconi Signal Generator

During this period, the construction of the final frequency control system for the Marconi Signal Generator was completed. Several circuit changes were made in various of the subassemblies to improve the performance of the system. The units were constructed to be mounted in a standard relay rack.

The unit was tested to determine the degree of frequency stabilization of the Marconi Signal Generator. The Berkeley Frequency Meter was adjusted to count the frequency with a sample time of 0.2 second at a rate of about one count per second. Typical frequency variations for frequencies between 150 and 300 mc/sec were ± 10 cps for periods of approximately 30 seconds (the time required for typical final adjustments in both measurement systems). Over long periods of time, the frequency difference between any two adjacent counts was less than 10 cps (the resolution of the Frequency Meter for a 0.2-second sample time). The short-term gain of the system was approximately 70 compared to the long-term gain of about 30. The reduction in long-term gain was due to drifts within the stabilization system.

The bandwidth of the stabilization system was originally several hundred cycles per second. The system was thus effective in reducing 60- and 120-cps frequency modulation as well as frequency variations caused by microphonics and random noise.

Early tests of the stabilization system indicated that the system did not introduce any internally generated periodic or random frequency variations. Later tests, however, disclosed an internally generated 60-cps modulation which was traced to the filament voltage of the Wang Confluxer vacuum tube. Conversion to d-c filament excitation on this tube eliminated this modulation. Apparently, internal Confluxer circuitry rather than the tube was responsible for the modulation as tubes with bifilar wound filaments showed equal modulation.

Another source of modulation introduced by the stabilization system was found to be heterodyne signals generated within the Berkeley Frequency Meter. Most of these signal components were at frequencies of several hundred cycles per second. An ideal cure for this difficulty would be to replace the Frequency Meter with a spurious-free heterodyne unit; however, this would be a major construction project and is not considered practical at this time. A temporary solution was to reduce the bandwidth of the stabilization system to a few cycles per second. This eliminated the unwanted frequency modulation but also reduced the effectiveness of the stabilization system at hum and microphonic frequencies.

During the latter part of this report period, the operation of the stabilization system became very poor. The difficulty was again traced to the Wang Confluxer. As the Confluxer cannot be repaired, a new unit is being procured.

Final circuit diagrams and descriptions of the stabilization system will not be reported until the system is again operating properly.

4. Equipment Failures

Several equipment failures, in addition to the difficulties reported above, have delayed work during this period. The major failures are described in the following paragraphs.

The operation of the Berkeley Frequency Meter was marginal and finally became intermittent. Several tubes were replaced and the instrument was completely realigned.

The Hewlett-Packard D-C Microvoltmeter showed excessive drift on the range which was used most with substitution measurement system. This trouble was traced to a cold-solder connection in one of the resistive networks used on this scale.

The output of the Marconi Signal Generator became excessively unstable at times both in frequency and amplitude. The cause of this instability has not been determined. The instrument is presently used only at the random times when the instability is not excessive.

C. Phase III. Aging of Quartz Resonators

1. Introduction

This phase of the work, assigned the Project No. A-402-13 by the Engineering Experiment Station of the Georgia Institute of Technology, was initiated on 1 March 1959 and is a continuation of the work prior to that date under Contract No. DA-36-039 SC-78910, Georgia Tech Project No. A-402-3. The work undertaken on 1 March under Contract No. DA-36-039 SC-78905 was subsequently expanded under Modification No. 1 to the Contract and renewed for an additional period of 12 months starting 1 July 1959, under Modification No. 4. This report, for the period from 1 October 1959 to 31 December 1959, represents a continuation of the work described in the Interim Report and in Report No. 2 (Quarterly) for the preceding periods of the current contract.

The fabrication and measurement of 16.25-mc resonators, operated in the fundamental mode, have been continued. Because of the lack of renewal of support of work on the 100-mc resonators the effort rate on the 100-mc program has been reduced and only one constant temperature, 55°C, has been maintained in operation. Instrumentation for measurements of resonators at 100 mc has been completed and one group for operation at the fifth overtone has been fabricated.

2. Apparatus

a. Modification of Crystal Impedance Meter TSM-15. The VHF frequency bridge as developed here for measuring the frequency of 100-mc resonators was driven initially by a Developmental Crystal Impedance Meter built here under Contract No. DA-36-039 SC-56730. This was recently replaced with a standard Crystal Impedance Meter TSM-15.

The operation of the bridge with the TSM-15 Crystal Impedance Meter was unsatisfactory because of excessive backlash in the tuning mechanism and because of difficulty encountered in setting the crystal drive level. Modifications were undertaken to remedy these faults.

Since changes on the internal frequency drive mechanism were not desirable, the fine frequency adjustment for the tuning was made by adding a small air trimmer condenser across L1A (see Figure 17 of Handbook of Instructions for Test Set, Crystal Unit, Quartz AN/TSM-15). The trimmer is driven by a 48-1 antibacklash reduction gear.

The adjustment of the crystal drive level was improved by the addition of a 110K-ohm resistor in series with the ungrounded end of R-22. This action allows a maximum screen voltage variation of 0 to 25 volts over the full range of R-22.

b. Other Measuring Apparatus. All sections of the frequency measuring equipment, exhibited in Figure 29 of the preceding report (No. 2), now appear to be operating properly except item No. 5 (the full wave, 100-mc, twin-coaxial line). During the course of several measurements the line must be moved and flexed. The results of this action appear to be frequency deviations of as much as ± 1 part/10^7. A study is now being conducted to determine the exact magnitude of the error and a satisfactory method of eliminating it.

A 100-mc crystal in the 55°C oven was connected to the VHF bridge by means of semipermanent resonant twin-coaxial lines. This line was not moved during the period of the study. Frequency measurements, made several times daily, showed a maximum departure of 5×10^{-8} parts from the original frequency in a 5-day period. The measurements are believed to eliminate the coaxial line as the source of error. It is planned to install a semipermanent fixed line to eliminate movement of the line as a source of error in the measurement of frequency or series resistance.

3. Resonator Fabrication and Measurement

a. Resonators Fabricated During This Quarter. During the period of this report 38 resonators have been fabricated and inserted in the constant-temperature ovens for frequency measurement. These have consisted of the following units:

Unit Designation	No. Units Operated	Coating and Overcoating
8-1 to 8-10	10	Al + Au
9-1 to 9-18	14	Al + Al
10-1 to 10-16	14	Al + Cu

These units were fabricated in order to establish a desirable overcoating metal for aluminum-base-plated units and to check the repeatability of processing stable units.

Representative plots of data obtained are shown in Figures 13, 14, and 15. It is apparent that stable units can be obtained with any of these plating combinations provided careful and definite processing steps are rigidly maintained. The 3-hour vacuum bakeout appears to be a necessary requirement. The utilization of bimetal film electrodes appears to lead to a larger percentage of the completed resonator group exhibiting erratic behaviour than is noted when a single metal such as gold, silver or aluminum is the plating.

Copper was adopted as a possible coating and overcoating metal because of its high electrical conductivity and a density, 8.9 gm/cm^3, lower than that of gold and silver; it has not previously been thoroughly examined as a resonator coating by anyone so far as is known. It appears to hold promise as a plating material for units operated at overtone modes.

b. Resonators Fabricated Previously and Continued on Measurement. The following resonators previously fabricated have been continued on measurement during this quarter:

Group Designation	Units Measured	Coating
T	17	Al only
U	16	Al + Al
V	10	Ag + Ni
X	6	Al only (1-hour bakeout)
Y	9	Al only (2-hour bakeout)
Z	8	Al + Au
7-1	10	Al + Ag

These units have continued to give the general stabilities reported previously in the preceding report.

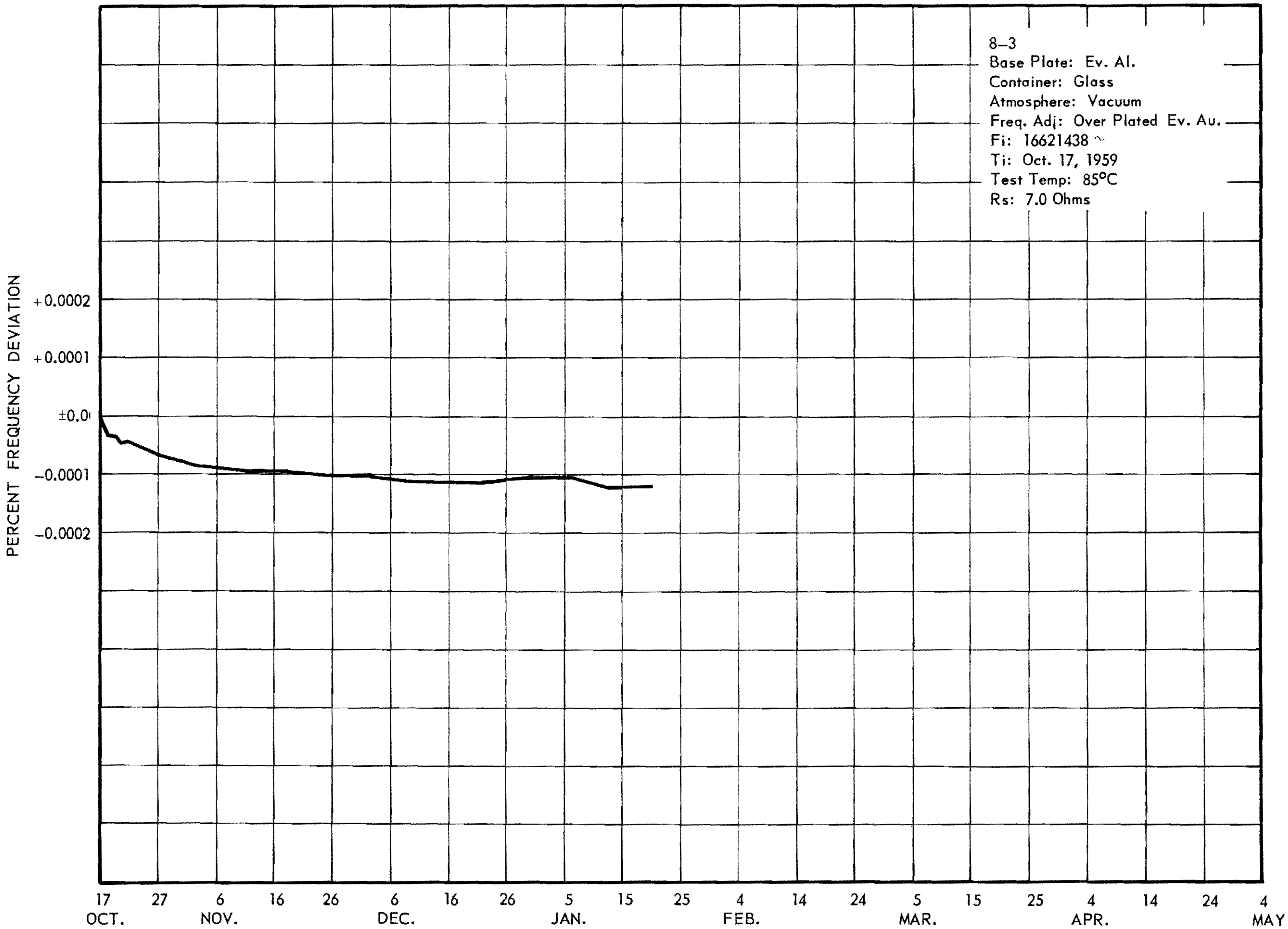


Figure 13. Plot of Frequency Data for Resonator 8-3 (Al + Au).

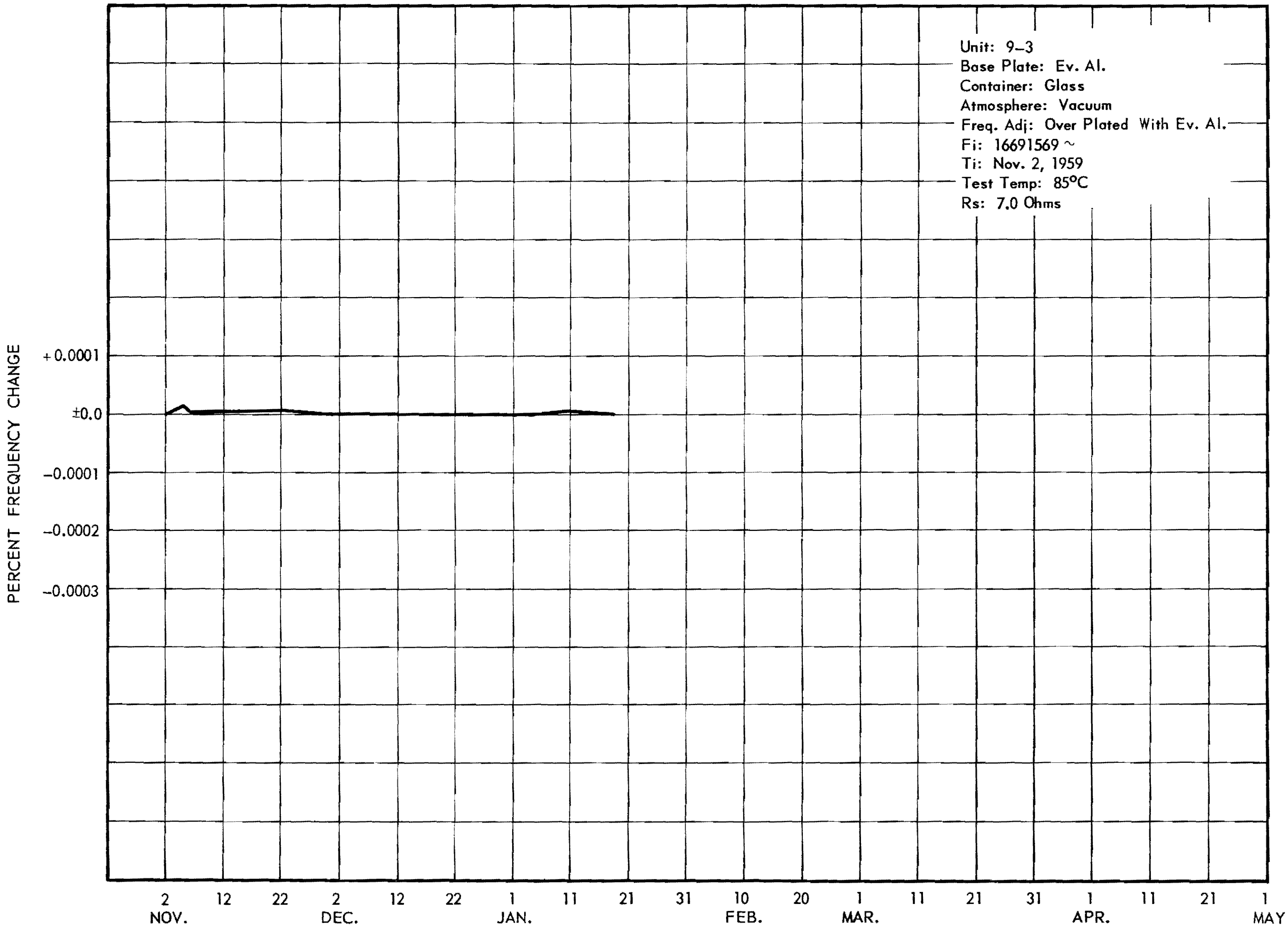


Figure 14. Plot of Frequency Data for Resonator 9-3 (Al + Al).

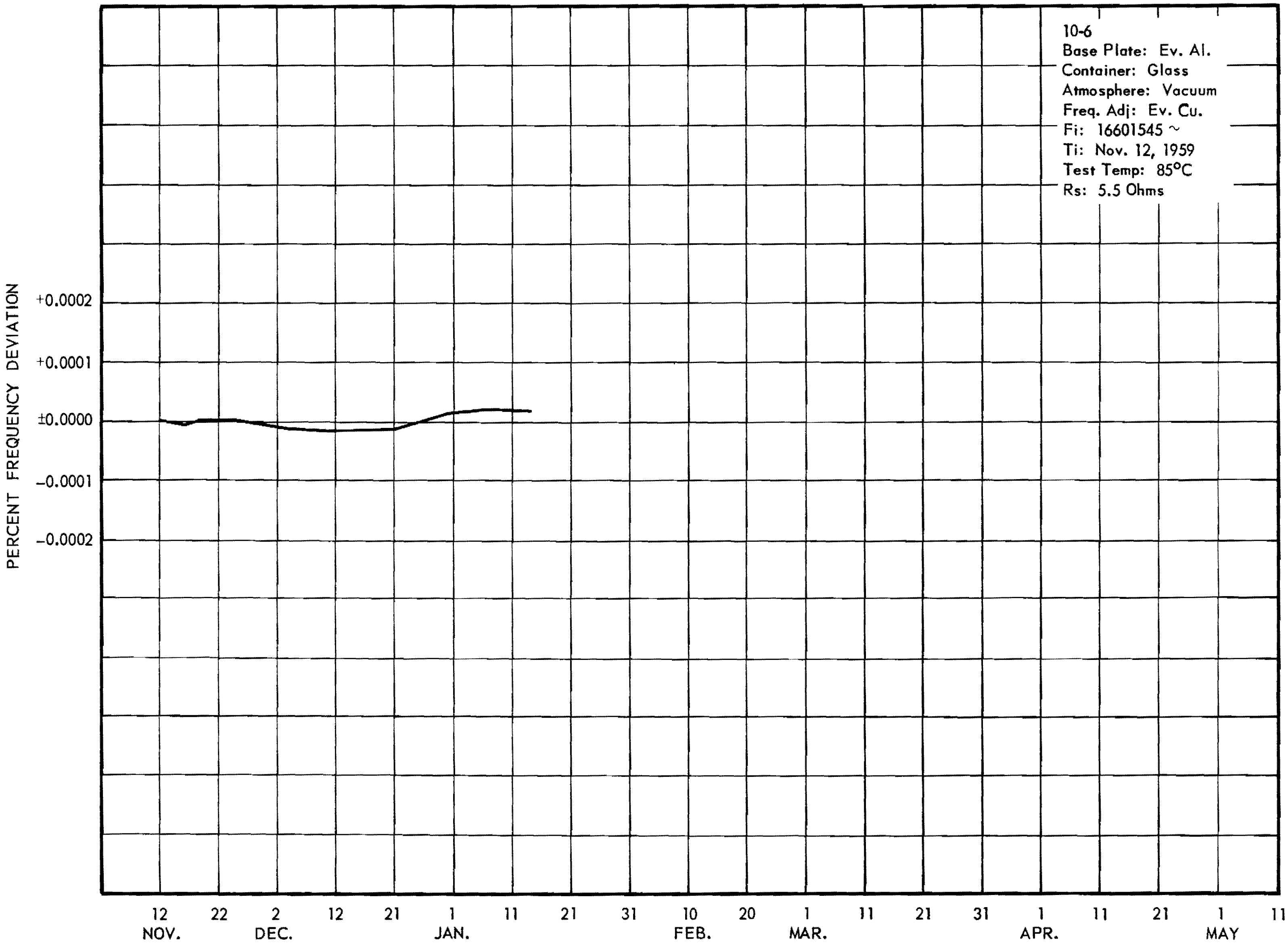


Figure 15. Plot of Frequency Data for Resonator 10-6 (Al + Cu).

c. Analysis of Frequency Data. The units of group T have continued with exceptional stabilities as exhibited for the specimen T-15 in the data of Figure 16. Reduction in bakeout times to 1 or 2 hours in lieu of three did not appear to be a proper step. Although some units of groups X and Y showed good stability, others did not. Hence the yield of good units was diminished.

The bimetal-plated resonators of groups Z and 7 gave some very stable units but those of group V did not. The yield of good units was affected as there were a number of erratic specimens in each group.

The yield of units for groups V, Z and 7 exhibiting a stability better than 0.5 ppm in the approximately 125 days of test is shown below.

Identification Group No.	No. Units	No. Units with Drift < 0.5 ppm in 120 days	Percent of Total Units of Group
V (Ag + Ni)	10	0	0
Z (Al + Au)	8	4	50
7 (Al + Ag)	10	5	50

Additional data for units fabricated and measured during the quarter are shown in Table II. The standard for each group (ppm drift during period of test) has been established to include a reasonable portion of the units of the group. The standard has been noted in the sixth column and the days measured are listed in the third column. It was maintained at < 1 ppm except for groups U and V. Large initial drifts followed by stabilization were noted for these units but the initial drift had to be allowed for in order to include any units as stable. The yield of stable units with bimetal platings was relatively small except for units of Groups 7 (Al + Ag) and 10 (Al + Cu). The yield of Group 8 was especially bad, possibly due to alloying effects initiated by plating

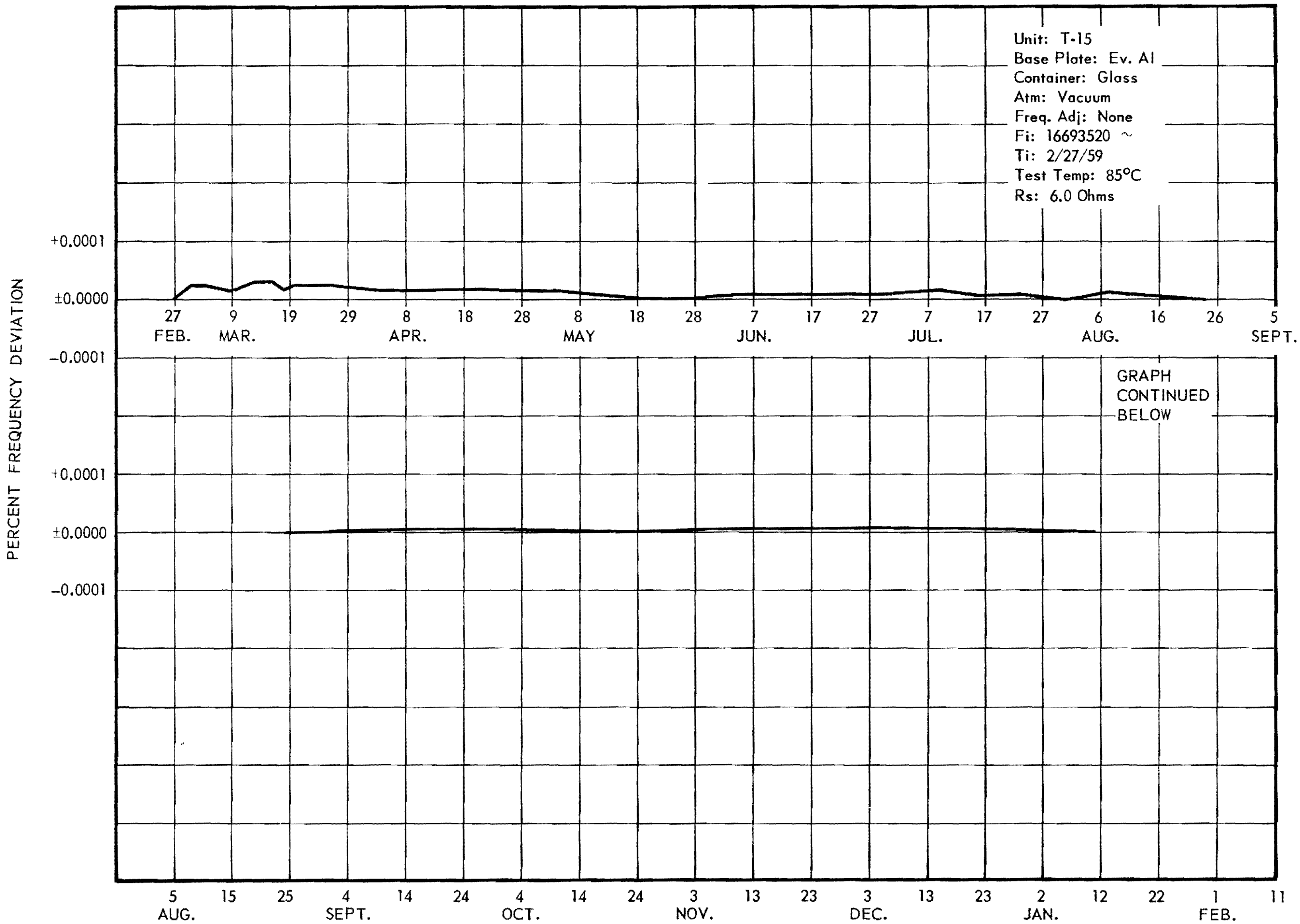


Figure 16. Plot of Frequency Data for Resonator T-15 (Al Only).

TABLE II

STABILITY ANALYSIS OF 16.25-MC QUARTZ RESONATORS
FABRICATED DURING LAST YEAR AND CONTINUED
ON MEASUREMENT DURING THIS QUARTER

Identification		Days Measured	No. Units Measured	No. of Good Stability	Standard for Group (PPM for Period of Test)	No. Erratic Units	Percent Erratic	Comments
Group	Plating							
T	Al only (3 hr.)	324	17	13	< 1	2	11.7	3-hour bakeout
U	Al + Al	305	16	11	< 2	0	0	
V	Ag + Ni	275	10	4	< 4	5	50.0	
X	Al only (high R_s)	150	6	1	< 1	3	50.0	1-hour bakeout
Y	Al only (2 hr.)	143	9	7	< 1	2	22.2	2-hour bakeout
Z	Al + Au	135	8	4	< 0.5	4	50.0	
7	Al + Ag	124	10	8	< 1	2	20.0	
8	Al + Au	90	10	1	< 1	1	10.0	Definite neg. slope (Au on hot substrate) 250°C
9	Al + Al	70	14	8	< 0.5	4	27.5	10, < 1 ppm
10	Al + Cu	60	16	10	< 0.5	2	12.5	13, < 1 ppm

the overcoating gold onto the hot aluminum film (250°C).

4. Summary

Measuring equipment for studies of 100-mc resonators was completed but only the 55°C constant-temperature oven was placed in operation.

Further studies of 16.25-mc resonators operated in the fundamental mode have shown that resonators plated with aluminum but not overplated may be fabricated that will maintain stabilities in the range of ± 1 ppm/yr, with a fair percentage showing drifts of < 0.5 ppm in the same period. A yield of 76.5 percent of 17 units gave drifts < ± 1 ppm/yr. On the other hand, units plated with Al + Al remained within the range ± 2 ppm/yr approximately and the better units exhibited drifts of < 1 ppm.

The factors required to achieve high stability for aluminum-plated units are: (1) rigid cleanliness; (2) deposition on a hot substrate (250°C); (3) mounting in glass; (4) vacuum bakeout at a temperature of approximately 180°C and at a pressure of $< 2 \times 10^{-5}$ mm of Hg for a period of 2 to 3 hours before seal-off.

Utilization of bimetal layers of Al + Au, Al + Ag, Al + Cu or Ag + Ni as plating materials resulted in units with less dependable stability characteristics, i.e., some were good and some were bad. Ag + Ni plating (Ni electroplated) gave units with a positive drift during the first 60 days of several ppm. This is associated with stress in the electroplated Ni film. Al + Au plating under some conditions gave downward drifts that implied triggering of alloying affects. Al + Ag and Al + Cu platings gave some units of excellent stability and a reasonable yield of good units. However, the latter two series have not been operated long enough to evaluate their actual yield over an extended period. The inference still remains that bimetal layers may be unsatisfactory for a maximum yield of units of long-term stability.

V. CONCLUSIONS

Under Phase I, the preparation of the mode charts for crystal D-1 has progressed rapidly. Most of the stronger modes of vibration have been identified as to the type of polarization in the three dimensional directions. Identification of several additional modes is anticipated as the x_o dimension is further reduced.

Under Phase II, the substitution measurement system has been evaluated as an instrument for determining the effective Q of a crystal. The accuracy of the system cannot yet be specified since it is greatly dependent upon the quality of the crystal to be measured. The errors appear to be less than 10 percent, however, for moderately good crystals in the frequency range from 200 to 300 mc/sec. The accuracies of resistance and frequency measurements are within the desired limits for a practical crystal test set. The system is also capable of determining the minimum crystal conductance, which reflects holder loss, and of determining the required antiresonating element value.

The Marconi Signal Generator frequency stabilization system, although not operating at the present time because of a component failure, has been evaluated and found exceptionally useful for both substitution measurements and Standard System measurements.

Under Phase III, equipment for the rapid measurement of 100-mc resonators operated in the 5th, 7th and 11th overtones at 0° and 55°C and in the temperature cycling range 0° to 55°C is now ready for use.

Resonators of 16.25-mc frequency, base plated with aluminum only, may be made which give a high yield of units able to maintain a drift of $< \pm 1$ ppm/yr; an appreciable yield of units drifting < 0.5 ppm per year may be anticipated.

Units base coated with aluminum and overcoated to frequency with aluminum will maintain drifts < 2 ppm/yr.

Employment of overcoatings of other metals for adjusting aluminum-base-plated units to frequency remains a doubtful procedure although a reasonable yield of stable units was obtained over a 60-day test period with resonators coated with the pairs Al + Ag and Al + Cu.

VI. PROGRAM FOR THE NEXT INTERVAL

Under Phase I, the preparation of mode charts for crystal D-1 as described in this report will be continued. Special fixtures will be prepared for obtaining similar data for 3-mc/sec crystals but as a function of upper electrode size rather than crystal size. Circular and square electrodes ranging in size from 3 to 28 mm will be used, respectively, with circular and square crystals.

Under Phase II, work will be directed primarily toward the study of high-frequency crystal-controlled oscillators. Some additional minor investigations of the substitution measurement system may be made after the Marconi Signal Generator frequency stabilization system is again in operation.

Under Phase III, fabrication of 16.25-mc quartz crystals, base plated with Al and overcoated with Cr or Cu, will be continued. Resonators plated with Cu only will be made. Fabrication and measurement of 100 mc resonators, base plated with Al only, will be initiated. Measurements of units already in storage in the constant temperature ovens will be continued.

VII. IDENTIFICATION OF KEY TECHNICAL PERSONNEL

Under Phase I, no changes in project personnel have occured during this report period. The personnel time is as follows:

NAME	TITLE	HOURS
Yasuo Tsuzuki	Assistant Research Engineer	480
S. N. Witt, Jr.	Assistant Project Director Research Engineer	80

Under Phase II, no changes in project personnel have occurred during this report period. The personnel time is as follows:

NAME	TITLE	HOURS
S. N. Witt, Jr.	Project Director Research Engineer	240
V. K. Woodcox	Research Assistant	480

Under Phase III, the primary personnel have remained unchanged during the period of thisreport. Mr. W. D. Dawson, a student assistant, was transferred to the project to assist in making frequency measurements. The personnel time for the period is as follows:

NAME	TITLE	HOURS
R. B. Belser	Project Director Research Associate Professor	24
W. H. Hicklin	Assistant Research Engineer	480
J. C. Meaders	Research Assistant	440
W. D. Dawson	Student Assistant	32

Respectfully submitted:

Samuel N. Witt, Jr.
Assistant Project Director
for Issac Koga, Project
Director, Phase I

Samuel N. Witt, Jr.
Project Director, Phase II

Richard B. Belser
Project Director, Phase III

Approved:

Arthur L. Bennett, Chief
Physical Sciences Division

VIII. APPENDIX

A. Addendum

The purpose of this project has been modified by Contract Modification No. 4 which became effective 1 July 1959. Accordingly, the PURPOSE section (pp. 1-3) of Report No. 2 (Quarterly) has been superseded by the PURPOSE of this report (No. 3).

B. An Improved Frequency Standard System

All three phases of this project depend upon frequency measurements as a vital part of the work. The present reference standard for frequency measurements is a Western Electric Type D175730 (O-76/U) Frequency Standard. This unit has been in operation at Georgia Tech for over nine years and records of its aging characteristics have been kept during this time. Occasionally, this standard has failed in operation but has been successfully repaired each time. Each failure, however, has resulted in poor frequency stability for several hours or days following the failure. During such times, measurements, particularly those of Phase III, were jeopardized.

The present standard is in need of repairs which include the replacement of vacuum tubes and also the replacement of the coarse oven thermo-switch. Such repairs will require the deactivation of this unit for such a period of time as to make the frequency stability poor for possibly several weeks. Because of the constant use of the unit, these repairs have not been made.

Also, to improve the absolute accuracy of the frequency standard system, additional Type O-76/U Standards are needed. One is required for offset frequency comparison with the 60-kc/sec standard broadcast of the National Bureau of Standards from Boulder, Colorado. A second additional unit will permit long-term time comparisons with Radio Station WWV to be made.

Two additional Type O-76/U Standards were requested. These units were received during the latter part of this report period. Plans have been formulated for the application of these units as mentioned above. The presence of three Standards will also permit the temporary deactivation of any one unit for repairs, as required.

Because of general interest of the Engineering Experiment Station in improving frequency control and reference techniques, a Station-sponsored project has been assigned the responsibility for designing and constructing the equipment necessary for improving the frequency standard system. A distribution system will also be constructed to provide each of the A-402-11, -12, and -13 laboratories with its required standard signals.

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Report No. 3 (Quarterly), Projects No. A-402-11, -12, and -13

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REPORT NO. 4 (QUARTERLY)

PROJECTS NO. A-402-11, -12, and -13

QUARTZ CRYSTAL STUDIES AND MEASUREMENTS

PHASE I. MOTIONAL PARAMETERS

By

ISSAC KOGA, YASUO TSUZUKI, and S. N. WITT, JR.

PHASE II. EQUIVALENT ELECTRICAL PARAMETERS

By

S. N. WITT, JR. and V. K. WOODCOX

PHASE III. AGING OF QUARTZ RESONATORS

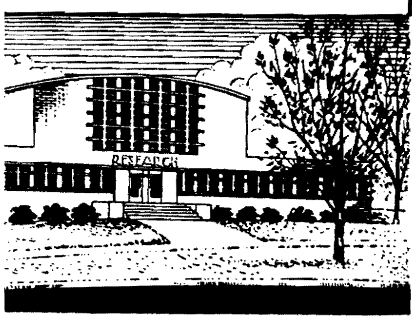
By

R. B. BELSER and W. H. HICKLIN

CONTRACT NO. DA-36-039 SC-78905

1 JANUARY 1960 TO 31 MARCH 1960

PLACED BY THE U. S. ARMY
SIGNAL RESEARCH AND DEVELOPMENT LABORATORIES
FORT MONMOUTH, NEW JERSEY



Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia

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Report No. 4 (Quarterly), 1 January 1960 to 31 March 1960, 59 pp. 28 Illus. Signal Corps Contract No. DA-36-039 SC-78905, Unclassified Report.

Under Phase I, measurements of the responses of the rectangular crystal in the vicinity of the third overtone were interrupted for a special study of circular crystals. Measurements of the spurious modes in the vicinity of the fundamental (3 mc/sec) indicated that the responses at frequencies lower than the fundamental increased rapidly in impedance as the diameter of the central electrode was decreased. At higher frequencies the changes appear to be relatively small but the results are uncertain because the interference of weak modes leaves the identification of specific responses in doubt. Experimental procedures were devised for the measurement of the charge distribution over the surface of the crystal at the fundamental frequency. Measurements of the change in the charge distribution as the size of the central electrode was reduced were begun.

Under Phase II, studies of the substitution crystal measurement system were discontinued at the beginning of this report period. The period was devoted to studies of high-frequency crystal-controlled oscillator circuits. Several oscillators were constructed, previous reports of this and other organizations serving as a guide. Several other oscillator circuit configurations were developed and prototype units constructed.

Typical instabilities of less than ±10 cycles per second for short periods of time were obtainable over the frequency range from 150 to 300 mc/sec. Some other oscillator characteristics were measured; however, the facilities for the full evaluation of the oscillator units have not yet been completed.

Under Phase III, 49 resonators of 16.5-mc frequency were fabricated and measured during the period. These consisted of 16 units plated with Al + Ag, 8 with Al + Cr, 6 with evaporated Cu, 4 with sputtered Au, 7 with sputtered Ag and 8 with evaporated Au. All were sealed in glass envelopes but in the latter group (evaporated Au) the base-to-envelope seal was made with an epoxy resin, Bondmaster No. 640. Approximately 100 units previously fabricated were continued on measurement.

Of those fabricated during the current quarter all were stable except the units plated

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The measurements of these resonators and the ones previously fabricated have indicated that stable resonators can be made by use of any of a number of metals or metal combinations as the plating, provided that cleanliness is observed in every detail of fabrication and provided that the seal does not leak.

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AD____________ Accession No.____________

Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia
QUARTZ CRYSTAL STUDIES AND MEASUREMENTS. PHASE I: MOTIONAL PARAMETERS, Issac Koga, Yasuo Tsuzuki, and S. N. Witt, Jr., PHASE II: EQUIVALENT ELECTRICAL PARAMETERS, S. N. Witt, Jr. and V. K. Woodcox, PHASE III: AGING OF QUARTZ RESONATORS, R. B. Belser and W. H. Hicklin.

Report No. 4 (Quarterly), 1 January 1960 to 31 March 1960, 59 pp. 28 Illus. Signal Corps Contract No. DA-36-039 SC-78905, Unclassified Report.

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ENGINEERING EXPERIMENT STATION
of the Georgia Institute of Technology
Atlanta, Georgia

REPORT NO. 4 (QUARTERLY)

PROJECTS NO. A-402-11, -12, and -13

QUARTZ CRYSTAL STUDIES AND MEASUREMENTS

PHASE I. MOTIONAL PARAMETERS

By

ISSAC KOGA, YASUO TSUZUKI, and S. N. WITT, JR.

PHASE II. EQUIVALENT ELECTRICAL PARAMETERS

By

S. N. WITT, JR. and V. K. WOODCOX

PHASE III. AGING OF QUARTZ RESONATORS

By

R. B. BELSER and W. H. HICKLIN

CONTRACT NO. DA-36-039 SC-78905

1 JANUARY 1960 TO 31 MARCH 1960

The object of this research is the enhancement of the understanding of the behavior of quartz crystals as frequency control and filter devices.

PLACED BY THE U. S. ARMY
SIGNAL RESEARCH AND DEVELOPMENT LABORATORIES
FORT MONMOUTH, NEW JERSEY

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(This report contains 59 pages.)

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LIST OF FIGURES (Continued)

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I. PURPOSE

The purpose of this contract is to advance the state of the art of applications of quartz crystals as frequency control and filter elements. Investigations and studies are conducted simultaneously in three areas of specialization:

Phase I. Motional Parameters

Phase II. Equivalent Electrical Parameters

Phase III. Aging of Quartz Resonators

Phase I is concerned with the study of motional parameters of thickness-shear and contour-shear modes of vibration of crystal plates. The purpose of Phase I is fourfold:

1. To continue the measurements of frequency and strain distributions of thin circular discs;

2. To measure frequency and strain distributions of plates having a smaller diameter-thickness ratio and adequately beveled to eliminate couplings with other modes;

3. To measure frequency and strain distributions of some triangular plates of the AT-cut; and

4. To conduct investigations which are concerned with the measurement of parameters of the equivalent electric circuit of circular plates, particularly to determine the influence of the electrode diameter and the motional capacitance constant, Γ, on the motional parameters.

Phase II is concerned with methods and techniques for determining the equivalent electrical parameters of quartz crystal units. The purpose of Phase II is threefold:

1. To continue the investigation of applications of crystal units in VHF and UHF oscillators for frequencies above 175 mc/sec to determine the following:

   (a) crystal parameters useful in oscillator circuit design,

   (b) methods and techniques for determining crystal parameters, and

   (c) test requirements for crystal units;

2. To design and construct experimental models of 175- to 300-mc/sec quartz crystal test sets capable of:

   (a) testing crystal units employing HC-6/U and HC-18/U holders,

   (b) determining the series resonant condition with a frequency accuracy of ±1 ppm,

   (c) indicating directly the crystal power dissipation with an accuracy such that the resultant frequency accuracy is ±1 ppm, and

   (d) operation with crystal power dissipation in the range 0.2 to 4.0 mw;

3. To perform studies and investigations leading to the development of methods and techniques for determining the equivalent parameters of crystal units in the frequency range of 300 to 500 mc/sec with emphasis on information pertinent to the eventual development of crystal specifications and crystal test sets.

Phase III is concerned with the effects of processing techniques and materials on aging of quartz crystal units. The purpose is threefold:

1. To fabricate experimental crystal units as follows:

   (a) AT-cut, fundamental mode, 16.0 mc/sec, gold and silver base plate, adjusted to frequency by evaporation or electrolysis of a second compatible metallic film, evacuated glass holders,

(b) AT-cut, third and fifth overtone modes, 48.0 and 80.0 mc/sec, evaporated aluminum base plate only, evacuated glass holders, and

(c) AT-cut, third and fifth overtone modes, 48.0 and 80.0 mc/sec, evaporated aluminum base plate, adjusted to frequency with evaporated aluminum, evacuated glass holders;

2. To measure for 6 months the frequency and resistance of crystal units stored at approximately 25°, 85°, and 125°C;

3. To determine, from an analysis of the data, the degree of compatibility of the frequency adjustment metal with the base plate metal.

In addition to the above requirements any other problems pertinent to the three phases which may arise during the course of the studies and which are mutually agreed upon between the contracting officer's technical representative and the contractor will be investigated.

II. ABSTRACT

Under Phase I, measurements of the responses of the rectangular crystal in the vicinity of the third overtone were interrupted for a special study of circular crystals. Measurements of the spurious modes in the vicinity of the fundamental (3 mc/sec) indicated that the responses at frequencies lower than the fundamental increased rapidly in impedance as the diameter of the central electrode was decreased. At higher frequencies the changes appear to be relatively small but the results are uncertain because the interference of weak modes leaves the identification of specific responses in doubt. Experimental procedures were devised for the measurement of the charge distribution over the surface of the crystal at the fundamental frequency. Measurements of the change in the charge distribution as the size of the central electrode was reduced were begun.

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III. PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

One publication, "The Alloying Behavior of Thin Bimetal Films, Successively or Simultaneously Deposited" was published by Mr. R. B. Belser in the Journal of Applied Physics, Vol. 31, p. 562, March 1960. A large part of the work reported was done under Contract No. DA-36-039 SC-42453 of the Signal Corps during the years 1953 and 1954.

No lectures or reports, related to this contract, have been presented other than as required by the contract.

On 21 January 1960, Mr. Dennis Pochmerski visited Georgia Tech to discuss progress and future plans on Phase II. A program for the construction and intercomparison of VHF and UHF crystal-controlled oscillators was agreed upon. Further work with the substitution measurement system was to be discontinued.

On 4 February 1960, Mr. R. B. Belser attended a conference with Dr. G. K. Guttwein, Mr. P. E. Mulvihill, Mr. J. M. Stanley, and Mr. M. Bernstein of USASRDL. Discussions concerning a revised satellite resonator program were held. The need for an Atomichron frequency standard was outlined and its possible availability for the program was established. A proposal on the research discussed was submitted to USASRDL on or about 24 February 1960.

On 24 March 1960, Mr. S. N. Witt, Jr., visited USASRDL for conferences with Dr. G. K. Guttwein and Dr. R. Bechmann concerning Phase I. Measurements on special crystals, as currently reported, were discussed. An immediate program to measure the fundamental polarization responses and spectra of 3-mc/sec beveled circular crystal plates as a function of electrode diameter was agreed upon. It was further agreed that the measurements of the special circular and rectangular unbeveled plates would be discontinued because of the high number of spurious responses.

On 25 March 1960, Mr. S. N. Witt, Jr., and Mr. V. K. Woodcox visited USASRDL for conferences with Mr. O. P. Layden and Mr. D. Pochmerski concerning Phase II. The previously and currently reported crystal oscillator studies were discussed. It was agreed that the studies of vacuum-tube oscillator circuits should be continued and that initial studies of transistor and tunnel diode applications should be initiated. It was also agreed that lower-frequency (below 200 mc/sec) oscillator circuits should be constructed for comparison of frequency stability, harmonic content, output amplitude, and other characteristics, with the higher frequency oscillators. In particular, the lower frequency oscillators should include harmonic multipliers to provide output energy at the higher frequencies.

IV. FACTUAL DATA

A. Phase I. Motional Parameters

1. Introduction

This phase of the work, assigned the Project No. A-402-11 by the Engineering Experiment Station of the Georgia Institute of Technology, was initiated on 1 March 1959 and is a continuation of the work prior to that date on Contract No. DA-36-039 SC-78910, Project No. A-402-1. This report is a continuation of the work described in the Interim Report, Report No. 2 (Quarterly), and Report No. 3 (Quarterly) for the preceding periods of the current contract.

The measurements of circular crystal plates in the vicinity of the fundamental frequency initiated under the previous contract were continued into the early part of the current contract period and were described in the Interim Report. Some preliminary measurements were made on beveled circular and triangular crystal plates. These measurements were described in Report No. 2 (Quarterly).

From September 1959 to January 1960 work was concentrated on the investigation of the behavior of a rectangular crystal in the vicinity of the third overtone. From a set of 16 rectangular crystal plates, two sensibly identical plates, D-1 and D-2, were selected for detailed study. Spectra of high dispersion over a frequency range of 70 kc/sec centered on the third overtone and of low dispersion over the interval of 800 kc/sec were recorded for crystal D-1 for x_o dimensions from the initial 24.56 to 23.75 mm in 112 steps during the previous two report periods. The polarization studies of the rectangular plates were described, together with the measurement equipment, in Report No.

3 (Quarterly). Many of the expected vibrational modes were identified.

The principal effort during the current report period has been the investigations of spectra and polarization patterns of special circular crystals. The size of the upper crystal electrode, rather than the size of the crystal plate, was varied in this study.

2. Studies of Rectangular Crystal Plates in the Vicinity of the Third Overtone Frequency

Spectrum and polarization measurements for crystal D-1 as a function of the x_o dimension have continued. During this report period, the x_o dimension of this crystal was reduced from 23.75 to 23.55 mm in 35 steps averaging less than 6 microns per step, for a total of 147 steps measured. The additional data will be presented in a later report. These studies were discontinued early in this report period to perform requested studies of special circular crystal plates. Further reduction is desirable to reach areas of interest.

3. Studies of Special Circular Plates Near the Fundamental Frequency

The purpose of the special studies of circular crystals in the vicinity of the fundamental frequency is to investigate the effect of changing the size of the electrodes. The charge distribution of the fundamental response over the surface and of some inharmonic responses will be investigated.

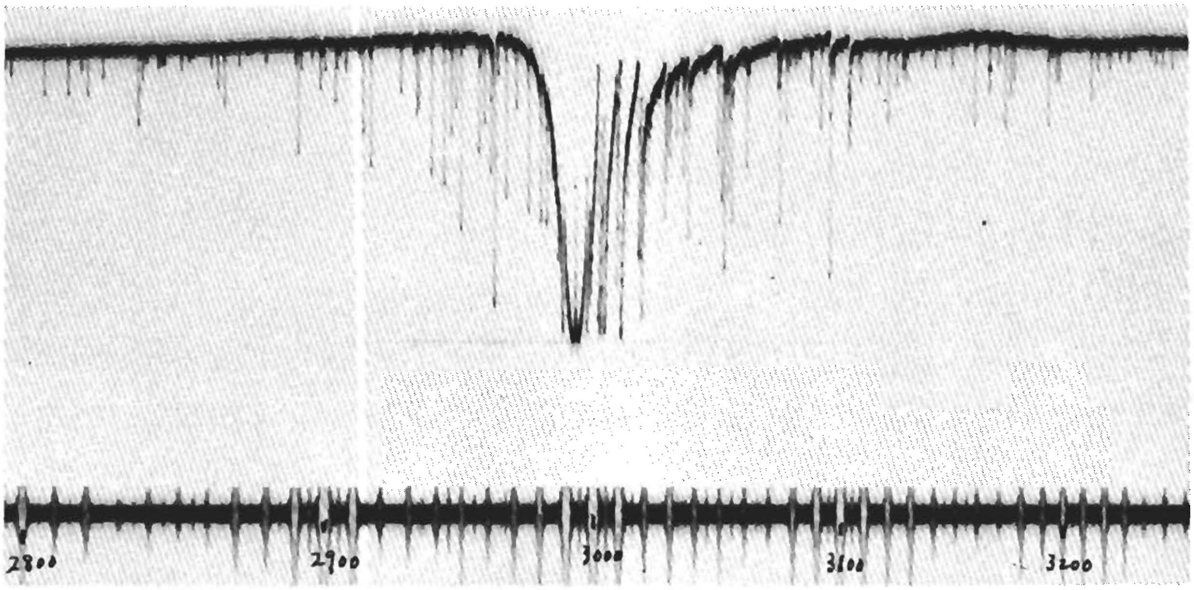
A total of nine unbeveled circular crystal plates with fundamental frequencies of 3 mc/sec and diameters of 28 mm were obtained. Since the x_o and z_o axes of the plates were not marked when received, they were located by polarized light to within an accuracy of 5 degrees. Later, X-ray measurements identified the axes to within one degree or less. Two of the plates with similar spectra were chosen. The one designated SC-1 was used for measurement.

Special electrodes of diameters from 3 to 24 mm (in steps of 3) and 28 mm were constructed. A spectrum of crystal SC-1 was obtained for each upper electrode diameter from 9 to 28 mm. The spectra for the 15- and 28-mm electrodes are shown in Figure 1.

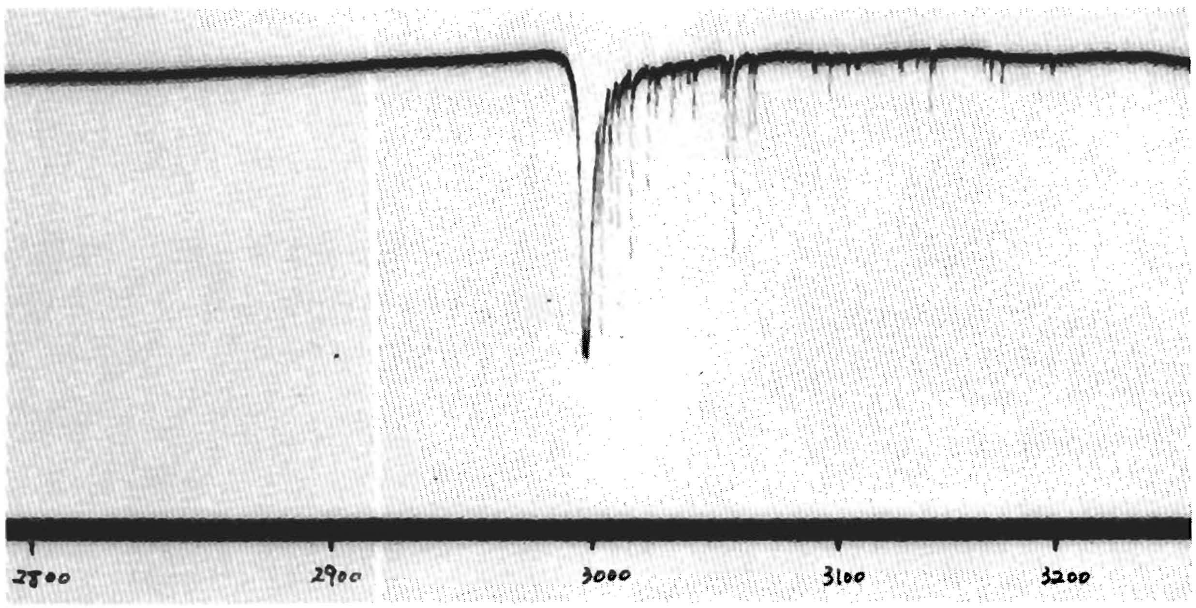
The impedance of each response was determined from the spectrum for the stronger responses in the vicinity of the fundamental, as indicated in Figure 2 by the code for the electrode of full crystal diameter, 28 mm. The spectra corresponding to the smaller electrodes were then measured and the corresponding impedances derived. It is noted that the impedance for the 24-mm electrode is substantially higher (often too high for measurement) for the responses at frequencies below the fundamental. Above the fundamental, however, the change is small and irregular. For the smaller electrodes, 21 mm and 18 mm, this trend continues.

Details of interpretation are obscured by the interactions of minor responses with the relatively strong responses that are being analyzed. The shift of frequency resulting from this interference leads to uncertainty in the identification of the responses measured with the smaller electrodes. Because of this uncertainty, it was decided to take advantage of the simpler response spectrum known to be available with beveled crystals.

Four beveled circular plates with specifications otherwise similar to the original nine plates were obtained. One of these was assigned the number SCB-1 and was used to obtain the spectra for electrode sizes from 12 to 28 mm, as shown in Figure 3. The absence of responses below the frequency of the fundamental thickness-shear response is evident. The recording of polarization patterns at the fundamental frequency is progressing and will be reported later.



(a) UPPER ELECTRODE OF 28 mm DIAMETER.



(b) UPPER ELECTRODE OF 15 mm DIAMETER.

Figure 1. Spectra of a Cylindrical Quartz Crystal 28 Mm in Diameter Near the Fundamental Frequency (3 Mc/Sec).

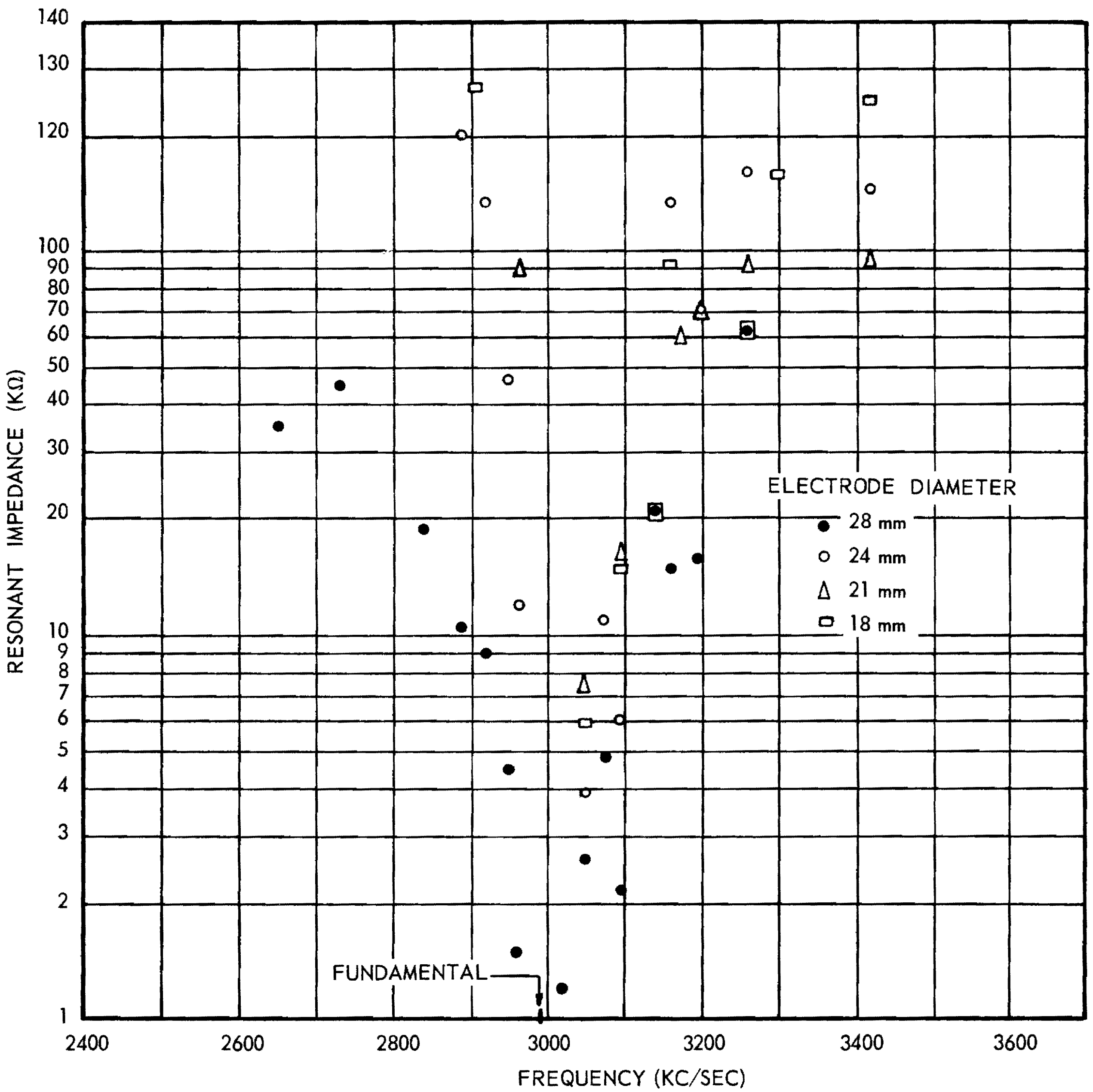
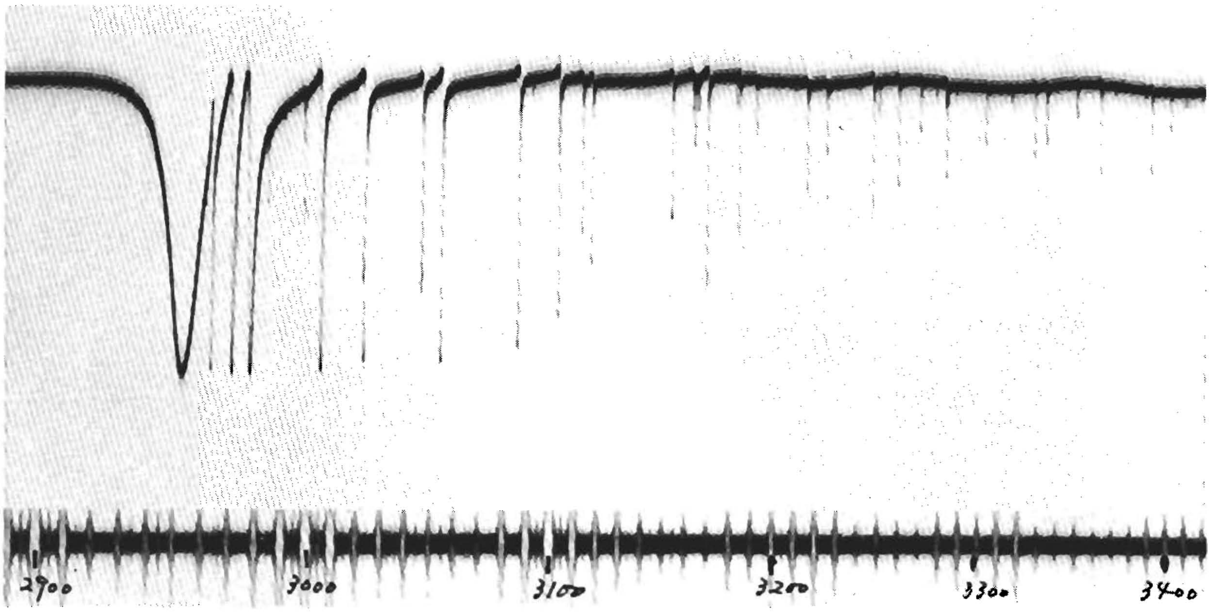


Figure 2. Measured Impedances of the Stronger Responses of a Cylindrical Crystal Near the Fundamental Frequency.



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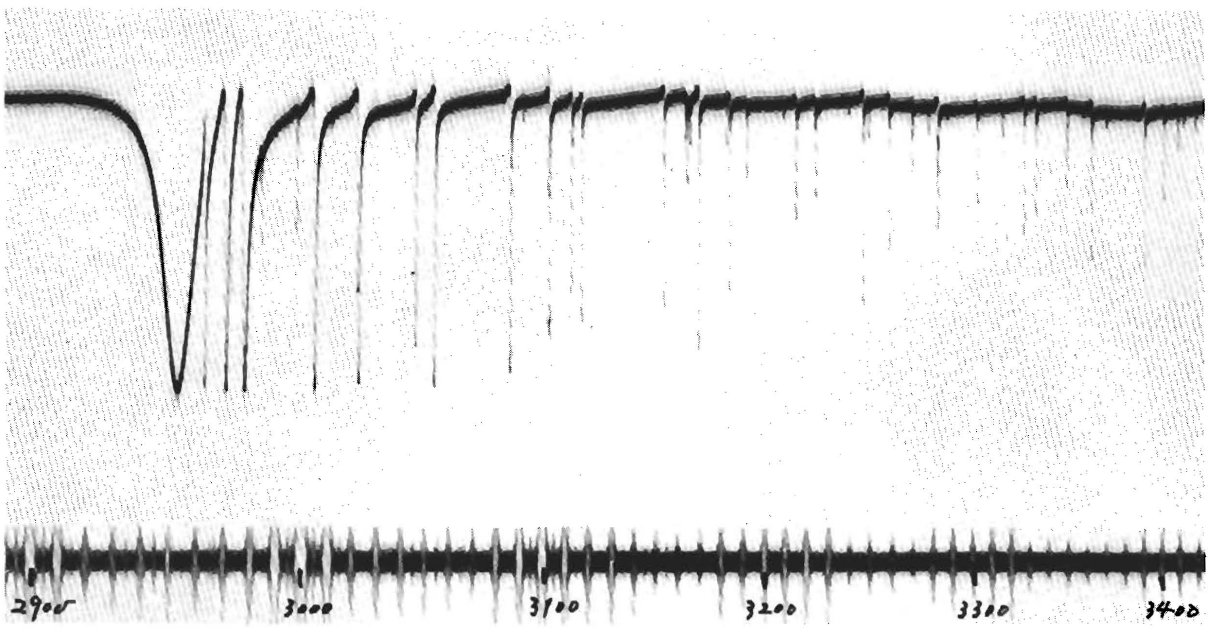
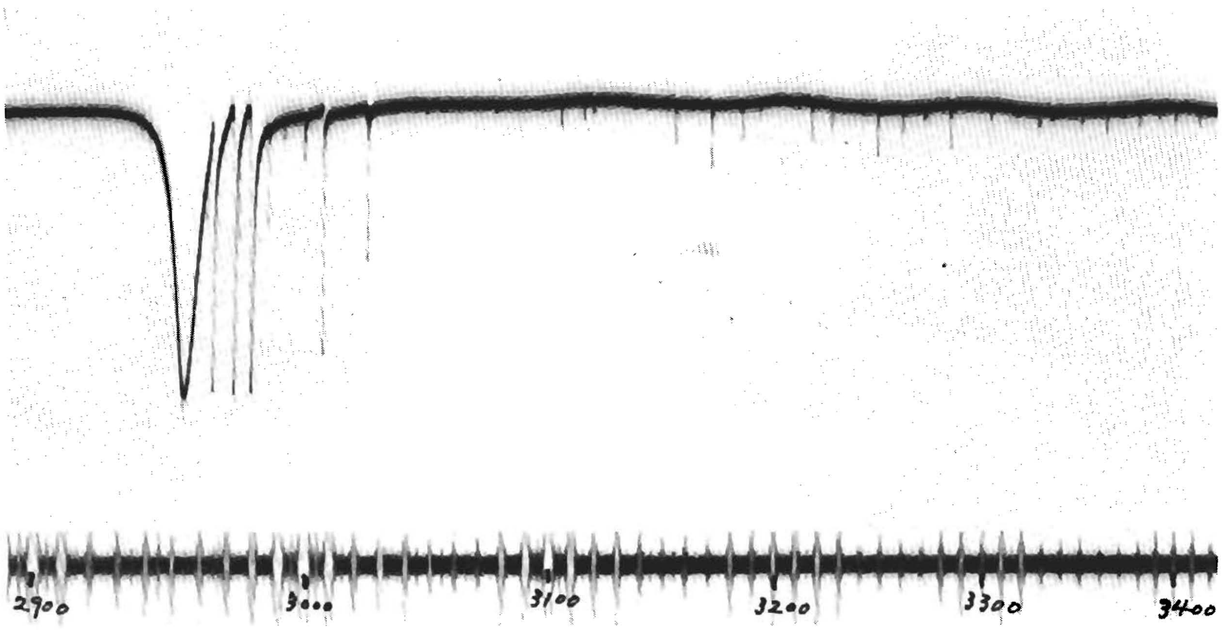
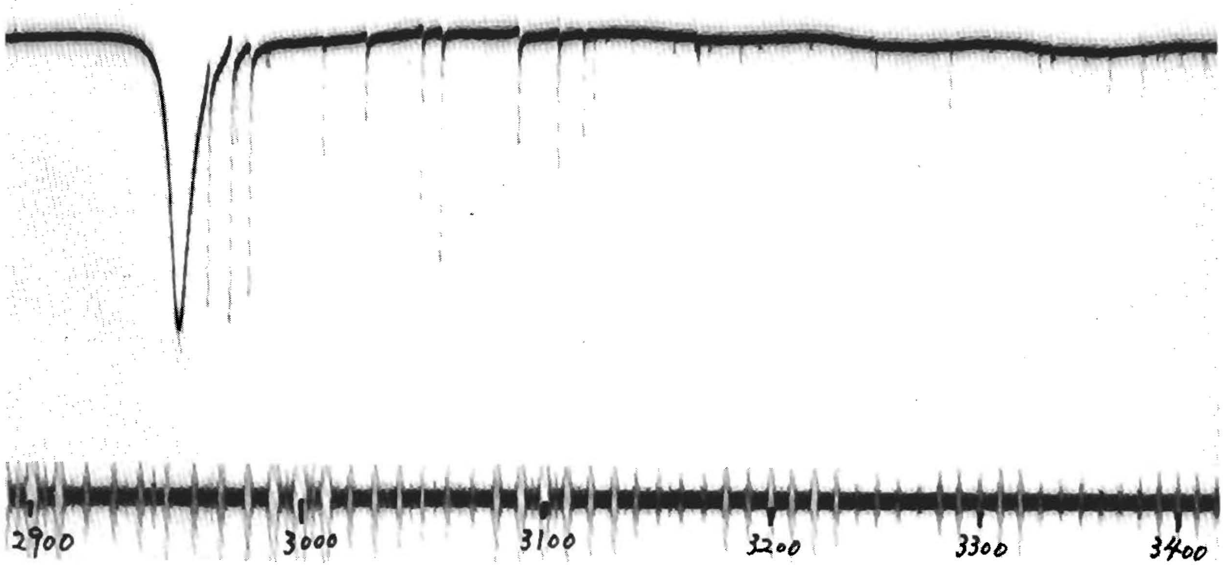


(b) UPPER ELECTRODE OF 24 mm DIAMETER.

Figure 3. Spectra of a Beveled Circular Quartz Crystal 28 Mm in Diameter Near the Fundamental Frequency (3 Mc/Sec).

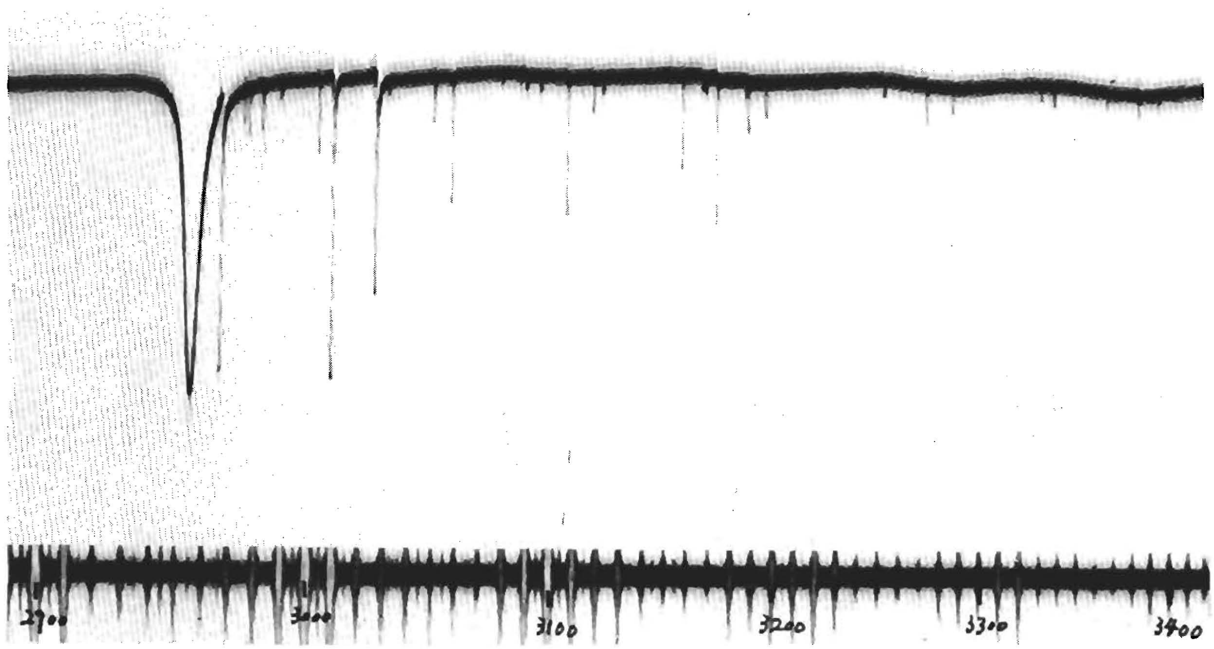


(c) UPPER ELECTRODE OF 21 mm DIAMETER.

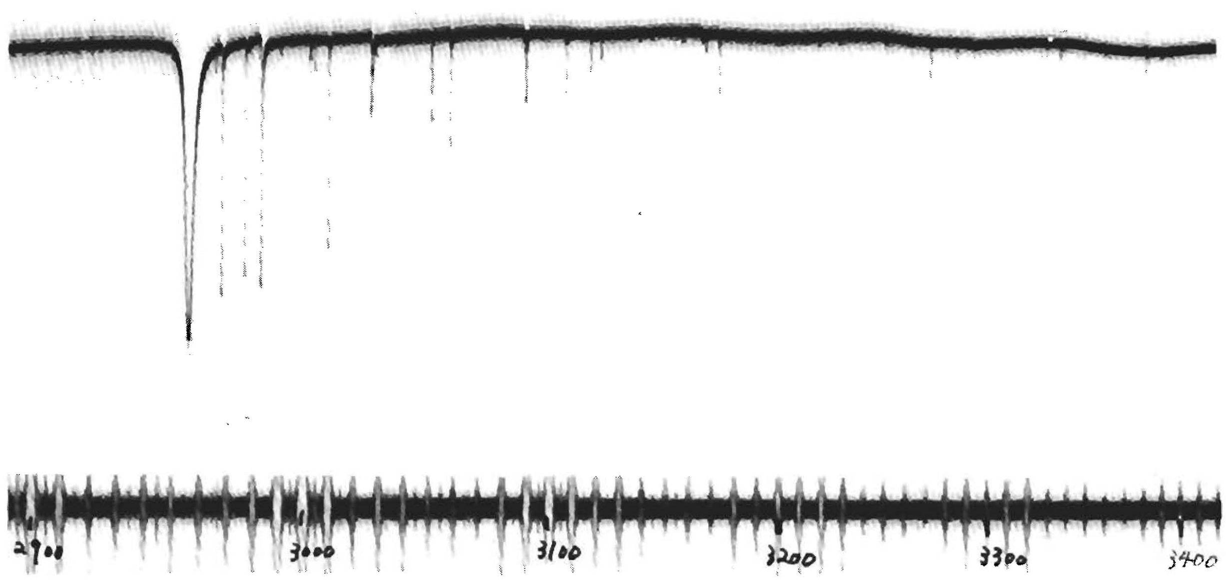


(d) UPPER ELECTRODE OF 18 mm DIAMETER.

Figure 3 (Continued). Spectra of a Beveled Circular Quartz Crystal 28 Mm in Diameter Near the Fundamental Frequency (3 Mc/Sec).



(e) UPPER ELECTRODE OF 15 mm DIAMETER.



(f) UPPER ELECTRODE OF 12 mm DIAMETER.

Figure 3 (Continued). Spectra of a Beveled Circular Quartz Crystal 28 Mm in Diameter Near the Fundamental Frequency (3 Mc/Sec).

4. Modifications of Measurement Procedures

The measurement of crystals at the 3-mc/sec fundamental rather than at the third overtone resulted in some tracking difficulties with the spectrum-recording equipment. The difficulties were resolved by connecting the crystal to a mid-tap on coil B of Figures 8 and 9 of Report No. 2 (Quarterly) rather than across the entire coil. The use of the tap required the recalibration of the equipment so that crystal resistance could be estimated. The required calibration curves are shown in Figure 4.

A series of spectra was recorded to determine the accuracy required in centering the small upper electrode. Figure 5 shows spectra for the electrode carefully centered, for the electrode displaced one millimeter in the x_o direction, and for the electrode displaced one millimeter in the z_o direction. Although the fundamental thickness-shear vibration is affected very little by the displacement, the differences are appreciable for some responses. Since the upper electrode can be conveniently centered to within about 0.3 mm, the error due to imperfect centering is negligible.

A more serious problem was that of measuring the polarization patterns with small upper electrodes. Measurements indicated that the true charge distribution is obtained only when a conducting area appears above the measurement probe. Without the conducting area, only the small voltage produced by the gradient component along the crystal surface is obtained.

At first, strips of silver were deposited on the surface of the crystal and aligned so that the strip remained over the probe as the crystal and upper electrode were moved together. The main electrode was then centered on the crystal, over the strip. Measurements indicate that a strip one millimeter wide has little effect on the measured charge distribution. Since the

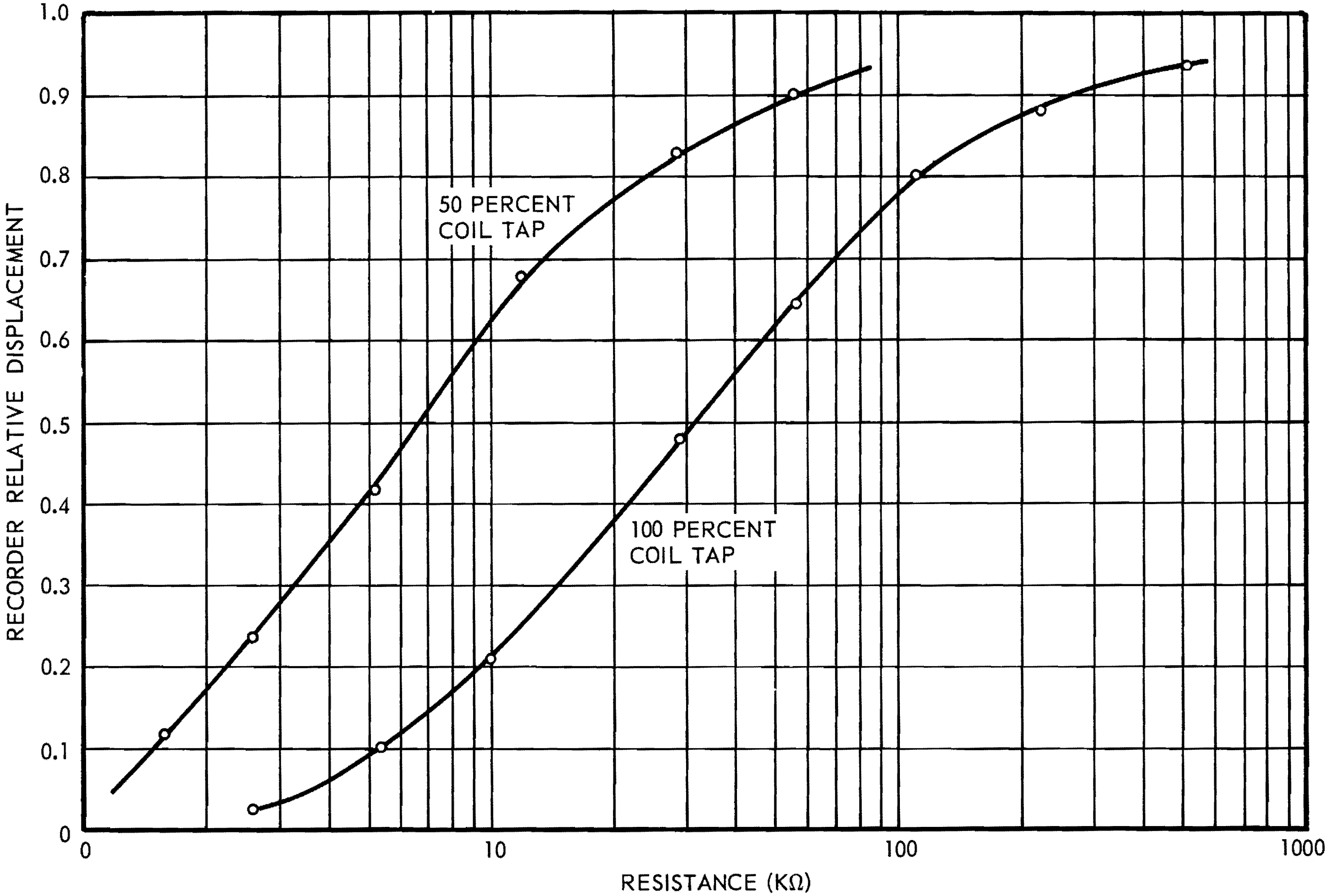
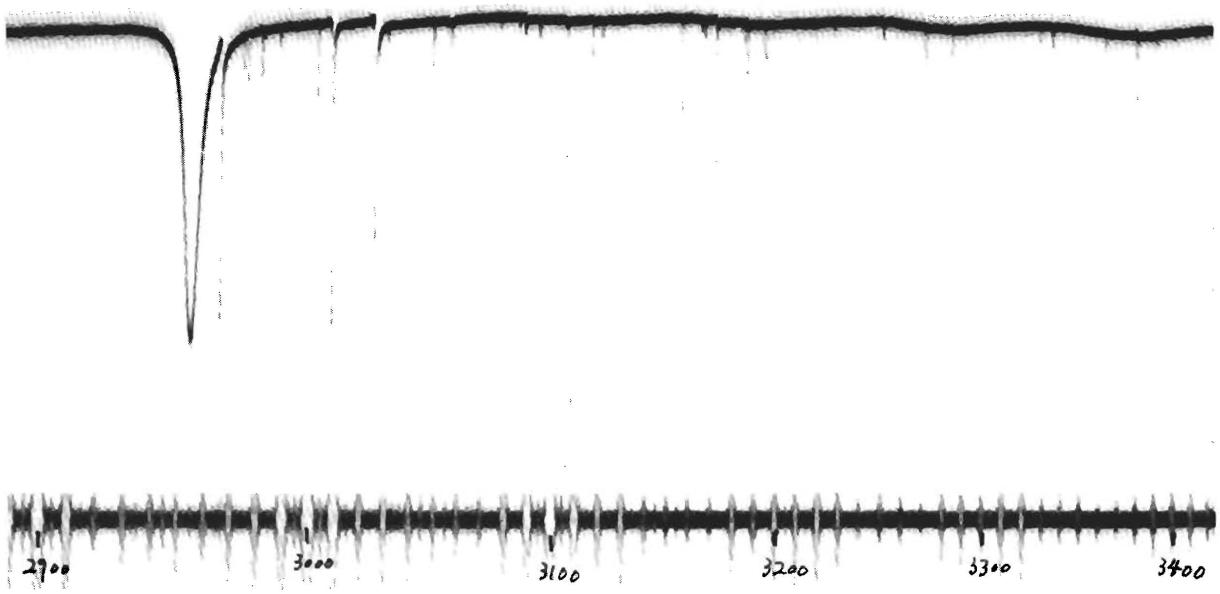
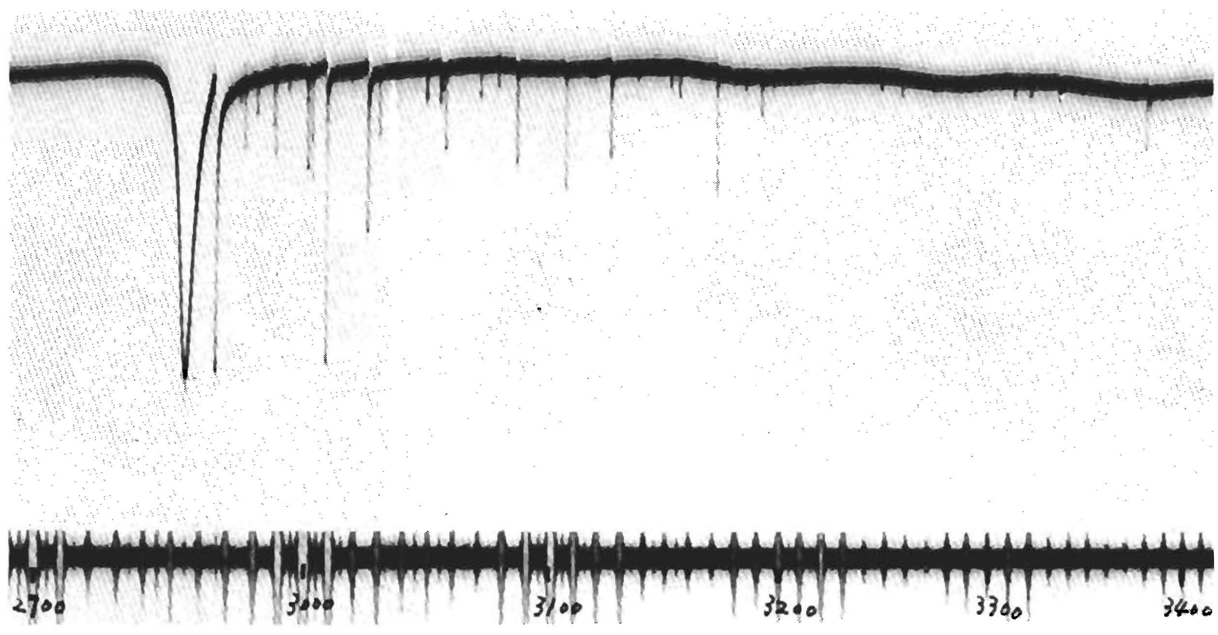


Figure 4. Motional Resistance Calibration of the Spectrum-Measuring Equipment.

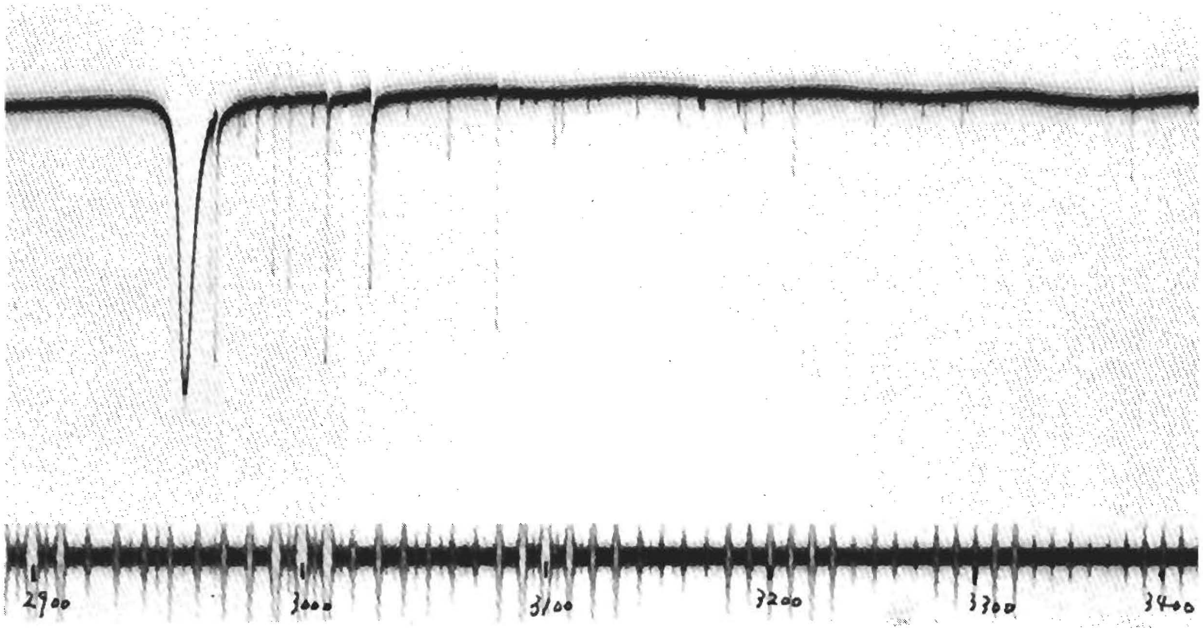


(a) CENTERED UPPER ELECTRODE.



(b) UPPER ELECTRODE DISPLACED 1 mm IN x_0 DIRECTION.

Figure 5. Spectra of Beveled Quartz Crystal with Electrode 15 Mm in Diameter.



(c) UPPER ELECTRODE DISPLACED 1 mm IN z_0 DIRECTION.

Figure 5 (Continued). Spectra of Beveled Quartz Crystal with Electrode 15 Mm in Diameter

measurement of polarization over the whole surface would require many strips, an alternate procedure was devised. An electrode 3 mm in diameter, resting on the crystal, was restrained so that it remained in a fixed position above the probe. Since the solid electrodes in use would interfere mechanically with the small fixed electrode, a centered electrode of silver was evaporated on the surface of the crystal. The crystal and the evaporated electrode can now be moved to any position relative to the probe and the fixed back-up electrode.

Initial polarization studies with the fixed electrode and plated centered electrode resulted in a distortion of the fundamental thickness-shear charge distribution. This distortion was traced to a frequency shift of the crystal response caused by the changing position of the fixed electrode. Current attempts to reduce this distortion include the replacement of the signal generator and buffer amplifier of Figure 4 of Report No. 3 (Quarterly) by an oscillator controlled by the crystal under test.

B. Phase II. Equivalent Electrical Parameters

1. Introduction

This phase of the work, assigned the Project No. A-402-12 by the Engineering Experiment Station of the Georgia Institute of Technology, was initiated on 1 March 1959 and is a continuation of the work prior to that date on Contract No. DA-36-039 SC-78910, Project No. A-402-2. This report, for the period 1 January 1960 to 31 March 1960, represents a continuation of the work described in the Interim Report, Report No. 2 (Quarterly), and Report No. 3 (Quarterly) for the preceding periods of the current contract.

A substitution system for measuring the parameters of quartz crystals at high frequencies was described in previous reports under this contract. Comparisons between substitution measurements and Crystal Measurement Standard measurements have shown maximum disagreements of less than 4 percent for resistance and less than 0.0002 percent for frequency. The Q' measurements have generally disagreed by less than 10 percent for crystals having reasonably good Q's. The current step-by-step procedure for making the substitution measurements was described in Report No. 3 (Quarterly). Further work with the substitution measurement system was discontinued at the beginning of the current report period.

Some investigations of high-frequency oscillator circuits have been reported on the current contract as well as on previous contracts. The primary efforts of the current report period have been the further investigations of oscillator circuits.

2. The Substitution Measurement System

Further development effort on the substitution measurement system was discontinued at the beginning of this report period. Crystal data obtained from the system during previous periods has, however, been found to be most useful in the design of oscillator circuits. The system has been left assembled and in operating condition to provide necessary data on new crystals or on previously unmeasured crystals.

A new substitution measurement crystal mount, duplicating the one described in Report No. 3 (Quarterly), was constructed and sent to USASRDL for evaluation.

3. High-Frequency Crystal-Controlled Oscillators

a. Introduction. The initial effort of the investigation of high-frequency oscillator circuits consisted of reviewing available literature, including previous reports on this and prior contracts. Existing oscillator units, constructed on this and prior contracts, were again placed in operation. Previously, beat-frequency techniques had been used to confirm the presence of crystal-controlled oscillations. A recognizable audio tone from a heterodyne frequency meter indicated crystal control whereas the absence of such a tone and, particularly, the presence of a high noise level indicated a non-crystal-controlled oscillation having random frequency variations of several hundreds or thousands of cycles per second. A re-evaluation of this method indicated that the presence of squegging could not generally be detected. When the frequency is counted on a Berkeley frequency meter system, any squegging becomes evident because of nonlinearitites in the system.

When again placed in operation, many of the previously constructed oscillators were found to squegg. The squegging rate was typically between 50 and 400 kc/sec. Similar difficulties were encountered with many of the recently constructed oscillators described in this report.

Many attempts were made to eliminate the squegging of the various oscillators by conventional means. These attempts included changing the values of grid coupling capacitors and grid return resistors, changing the plate and cathode by-pass and decoupling components, shifting the ground points and grounding methods, and changing components in the r-f circuits. Methods were not found to eliminate the squegging of some of the oscillators.

Changes in r-f circuitry were found to be more effective in reducing the squegging than changes in by-pass components. For example, with all of the oscillators except the capacitance-bridge oscillator, inductors were used in parallel with the crystals to provide antiresonance. This action is illustrated in Figure 6 where an uncompensated crystal response and a properly compensated response are shown. Any choice of compensating inductor which placed the crystal response at positions other than approximately centered on the conductance axis generally produced squegging.

No other general difficulties were encountered in the construction of oscillators; however, each oscillator showed various individualities which will be discussed later.

Each oscillator was tested with a sufficient number of crystals to determine roughly the frequency range of operation and the required crystal quality. Figure 6 serves to define the terms R_{max} and R_{min} as used in the descriptions of the oscillators. The frequency of operation was generally near the fre-

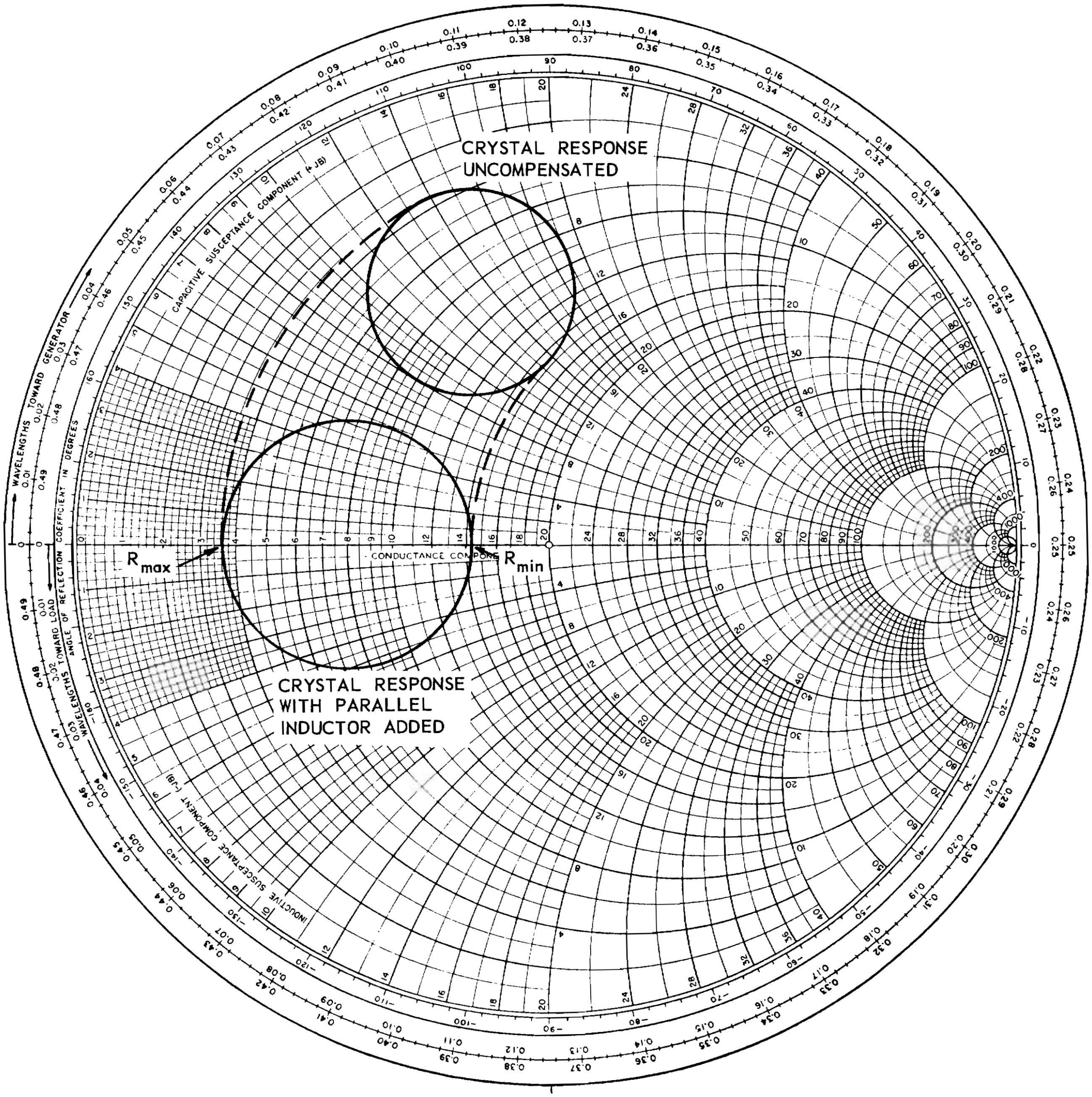


Figure 6. Inductive Crystal Compensation.

quency at which R_{min} occurred, as indicated by the substitution measurement system.

Some of the references which were found useful in the oscillator design work are listed in the BIBLIOGRAPHY TO PHASE II (Section VIII).

b. The Cathode-Coupled Oscillator. The cathode-coupled oscillator circuit is a lower-frequency crystal-controlled oscillator circuit investigated and described by Armour.[1] A model of this oscillator was constructed to operate at 150 mc/sec by following the detailed steps outlined by Armour. Specifications of wire size, spacing, number of turns, and other details were closely followed. When the coils were checked on a Boonton Model 160A or Model 170A Q-Meter, the values agreed very closely with those specified. However, in the circuit, the required inductances differed widely. Because of differences in stray capacitances, the values of inductances had to be changed by as much as 50 percent to obtain proper operation. After following Armour's tune-up procedure, the oscillator was satisfactorily crystal controlled at 150 mc/sec. Output was obtained by loosely coupling a pick-up coil to the plate inductance of one of the tubes. After amplification by two IFI Model 530 wide-band amplifiers, the output frequency was counted directly by the Berkeley frequency meter and converter. Because of nonlinearities (possibly in the wide-band amplifiers) some output was available at 300 mc/sec. A photograph of this oscillator is shown in Figure 7.

Armour does not give design procedures for the construction of oscillators for frequencies above 150 mc/sec. However, from the same basic circuit con-

[1]See Section VIII, Reference 1.

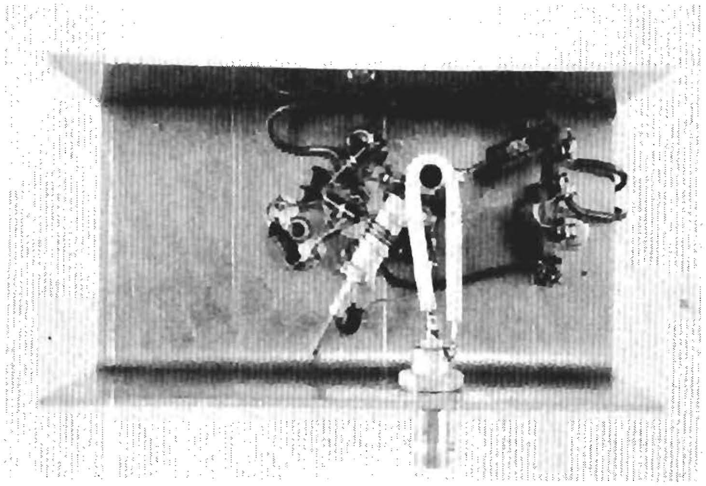


Figure 7. The 150-Mc/Sec Cathode-Coupled Oscillator

figuration with reduced lead lengths and inductances scaled from the 150 mc/sec unit, an oscillator which operated satisfactorily with crystal FA-89 at 217 mc/sec was constructed. A photograph of this oscillator is shown in Figure 8. The crystal was moved to the underneath side of the chassis to reduce the lead lengths and to reduce the heating from the vacuum tube. Instabilities due to heating of the crystal had been observed for the 150-mc/sec oscillator.

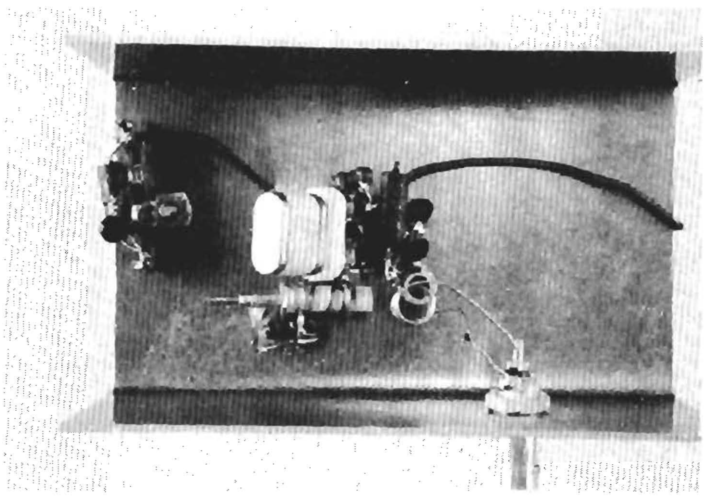


Figure 8. The 217-Mc/Sec Cathode-Coupled Oscillator

The circuit configuration (same for both oscillators) is shown in Figure 9.

ALL CAPACITANCE VALUES IN MICROMICROFARADS.
ALL RESISTANCE VALUES IN OHMS.
K = 1000

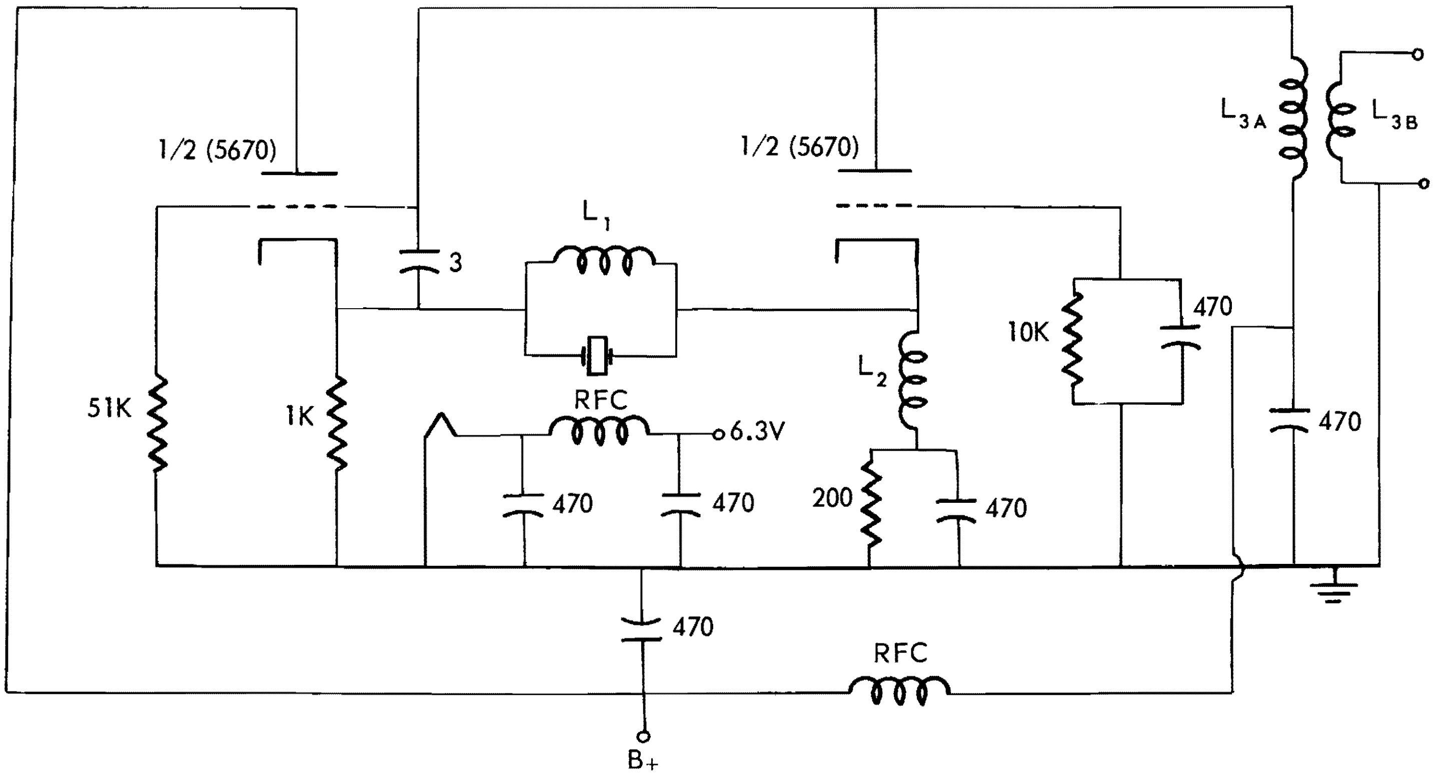


Figure 9. The Cathode-Coupled Oscillator Circuit Diagram.

Both the 150- and 217-mc/sec oscillators maintained typical frequency instabilities of less than ±10 cycles per second for periods of several seconds. Continuous recordings of frequency variations could not be made because of the lack of the necessary equipment. Likewise, facilities were not available for determining the effects of temperature changes.

c. The Capacitance-Bridge Oscillator. A capicitance-bridge oscillator unit,[2,3] originally described under Contract No. DA-36-039 SC-71191, was again placed in operation. A photograph of this unit with minor component modifications made to improve the tuning characteristics is shown in Figure 10. The basic circuit diagram of the unit is shown in Figure 11. The oscillator is tuneable from 200 to 250 mc/sec and was operated with crystal FA-89 at 217 mc/sec.

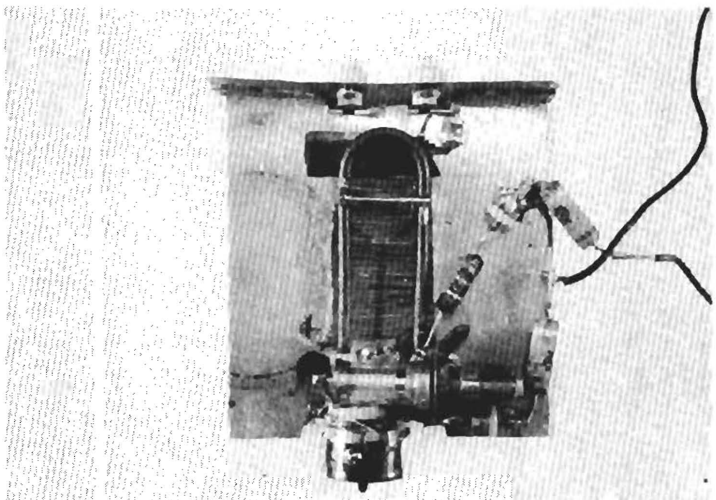


Figure 10. The 250-Mc/Sec Capacitance-Bridge Oscillator

Another variation of this oscillator was constructed to operate from 230 to above 300 mc/sec with a Mallory Inductuner as the chassis. One section of the Inductuner was used as the plate coil. The cathode coil was etched from a double-clad copper-laminated phenolic board with the cathode

ALL CAPACITANCE VALUES IN MICROMICROFARADS.
ALL RESISTANCE VALUES IN OHMS.
K = 1000

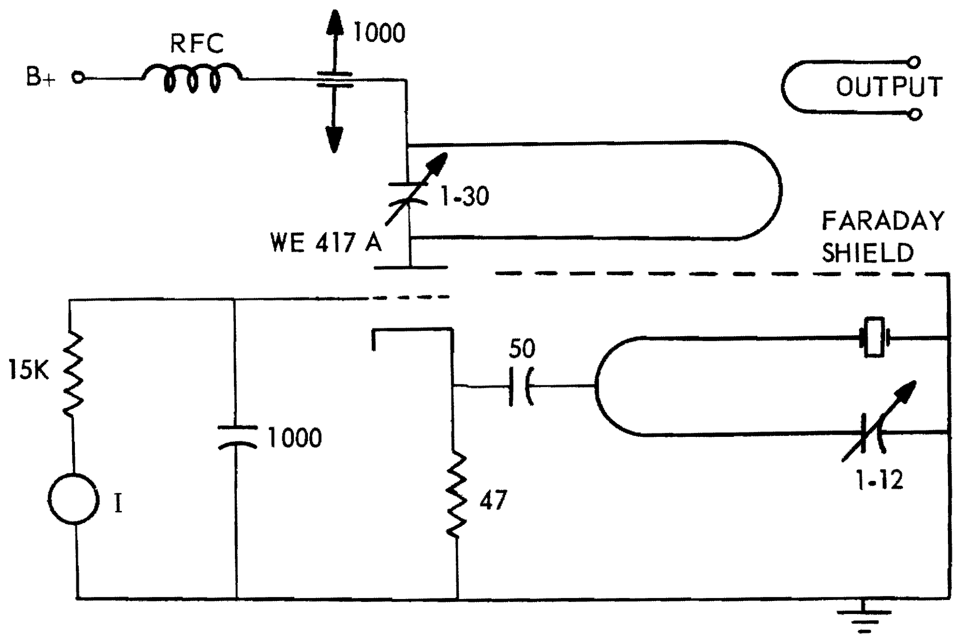


Figure 11. The Capacitance-Bridge Oscillator Circuit Diagram.

loop on one side and a Faraday shield on the other side. No provisions were made for tuning the cathode coil. Oscillations were never obtained with this unit, possibly because of insufficient coupling between the plate and cathode coils.

Still another model of the capacitance-bridge oscillator was constructed entirely on a tube socket. This method of construction which provided a minimum length of lead, is shown in Figure 12. Oscillations were obtained, but crystal control was not, probably because of the absence of a Faraday shield.

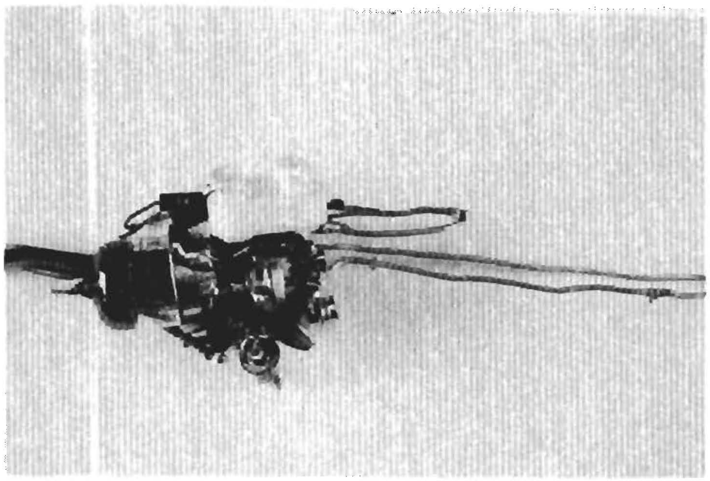


Figure 12. The Unitized Capacitance-Bridge Oscillator Circuit Diagram

Squegging was again observed with some forms of the capacitance-bridge oscillator.

d. The Plate-Degenerative Oscillator. Three plate-degenerative oscillator units[2,3] have been previously described under Contract No. DA-36-039 SC-71191. The total frequency range covered by the units is 140 to 330 mc/sec (140 to 220 mc/sec for the first, 200 to 300 mc/sec for the second, and 260 to 330 mc/sec for the third). The circuit diagram is shown in Figure 13 and is the same for all units, except for minor changes. A photograph of the

ALL CAPACITANCE VALUES IN MICROMICROFARADS.
ALL RESISTANCE VALUES IN OHMS.
K = 1000

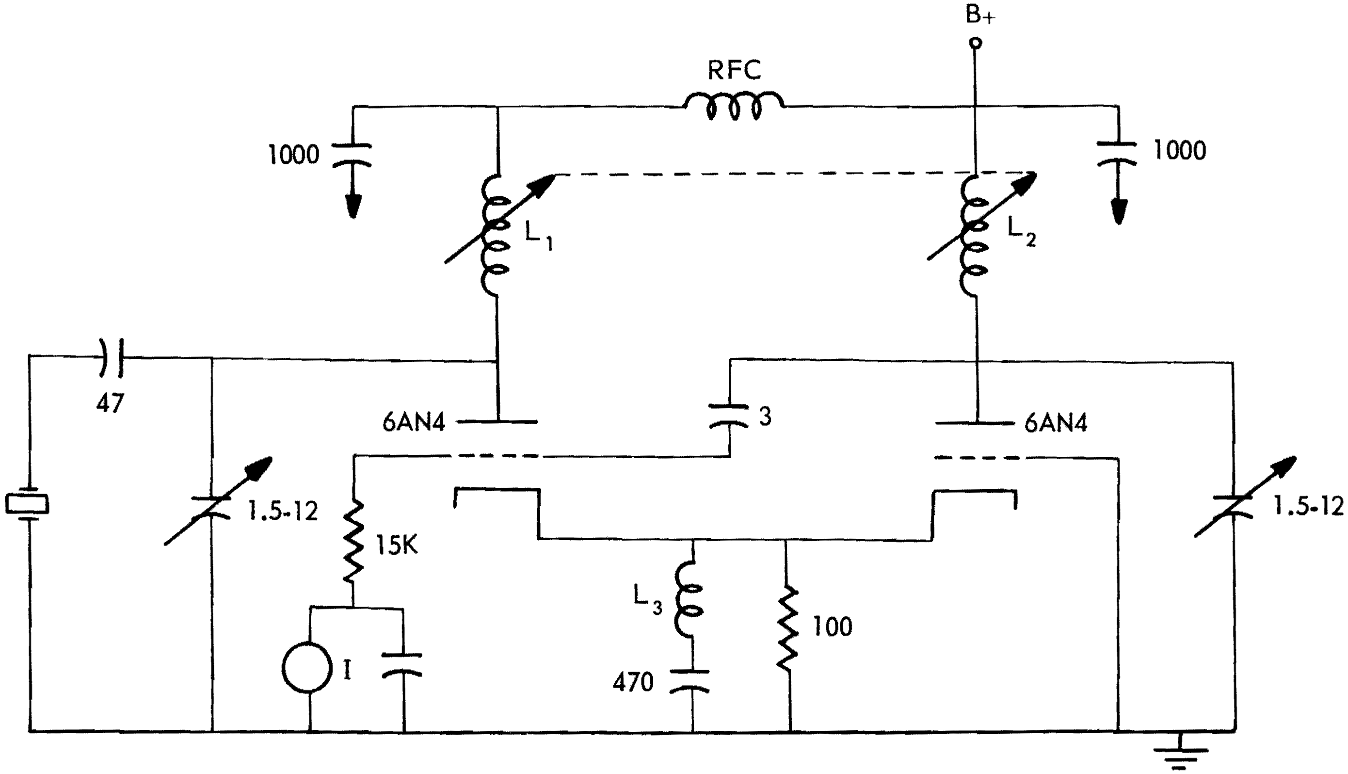


Figure 13. The Plate-Degenerative Oscillator Circuit Diagram.

second unit is shown in Figure 14.

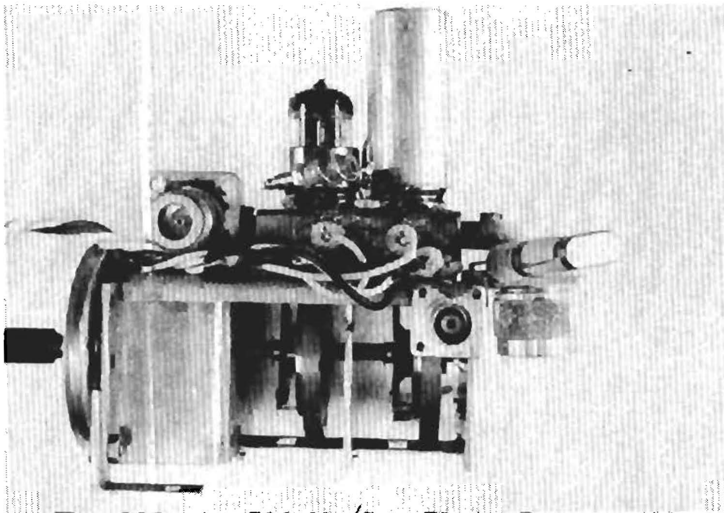


Figure 14. The 200- to 300-Mc/Sec Plate-Degenerative Oscillator

Crystal FA-89 was used in both the first and second units to obtain crystal-controlled oscillations at 217 mc/sec. The tune-up procedure for obtaining crystal control with the plate-degenerative oscillator was less critical than for any of the other oscillators but at the same time the stability was poorer. Squegging was also observed with the highest frequency unit.

e. The Grid-Degenerative Oscillator. The grid-degenerative oscillator is basically a grounded-grid oscillator with the grounding of the grid accomplished through a compensated crystal. The circuit diagram is shown in Figure 15. Over a moderate frequency range, the parallel resonant circuit consisting of the compensating inductance and the crystal capacitance produces a high-impedance antiresonance in the grid circuit to prevent oscillations. At the crystal overtone response, the grid is grounded by the resonant resistance of the crystal to provide the necessary condition for oscillations.

A fixed-tuned model of this oscillator was designed to operate at 250 mc/sec. Typical crystal resistances at this frequency were, however, too

ALL CAPACITANCE VALUES IN MICROMICROFARADS.
ALL RESISTANCE VALUES IN OHMS.
K = 1000

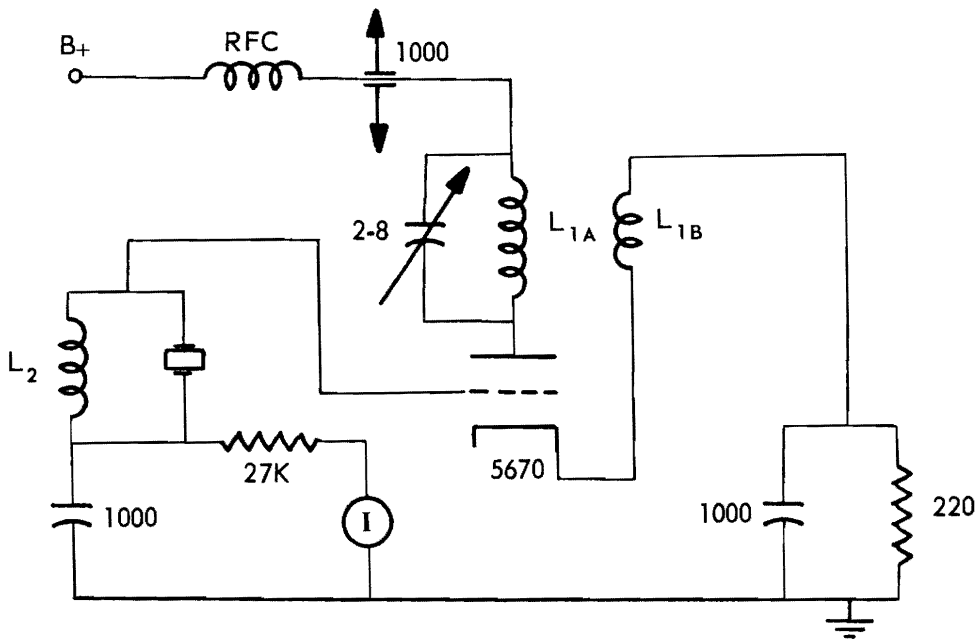


Figure 15. The Grid-Degenerative Oscillator Circuit Diagram.

high to permit oscillations to occur. Oscillations were readily obtained by replacing the crystal with a resistance or other low-impedance device. A photograph of a grid-degenerative oscillator is shown in Figure 16.

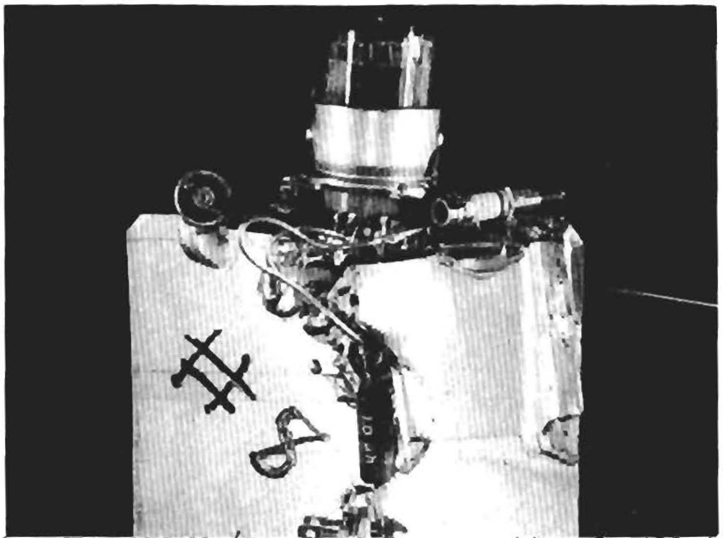


Figure 16. The 250-Mc/Sec Grid-Degenerative Oscillator

f. The Modified Grounded-Grid Oscillator. The modified grounded-grid oscillator is essentially a grounded grid oscillator with the crystal in series with the cathode feed-back path. The circuit diagram is shown in Figure 17. A model of this oscillator, tuneable over the frequency range from 200 to 250 mc/sec, was constructed. When the oscillator was tested, squegging occurred over the entire tuning range. The squegging was eliminated between the frequencies of 210 and 220 mc/sec by carefully positioning the cathode coil with respect to the plate coil. Crystals FA-89 and 6 both provided crystal control at 217 mc/sec. Crystal 12 provided control at 219 mc/sec. The stability of this oscillator was comparable to that of the cathode-coupled oscillator at 217 mc/sec. A photograph of this oscillator unit is shown in Figure 18.

g. The Cathode-Degenerative Oscillator. The cathode-degenerative

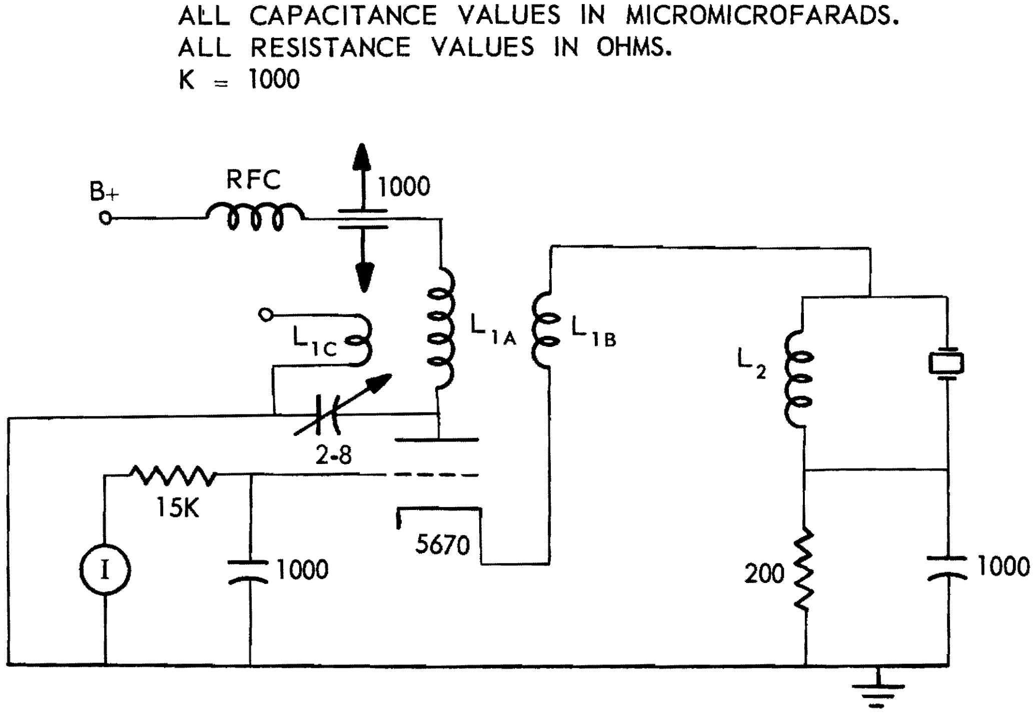


Figure 17. The Modified Grounded-Grid Oscillator Circuit Diagram.

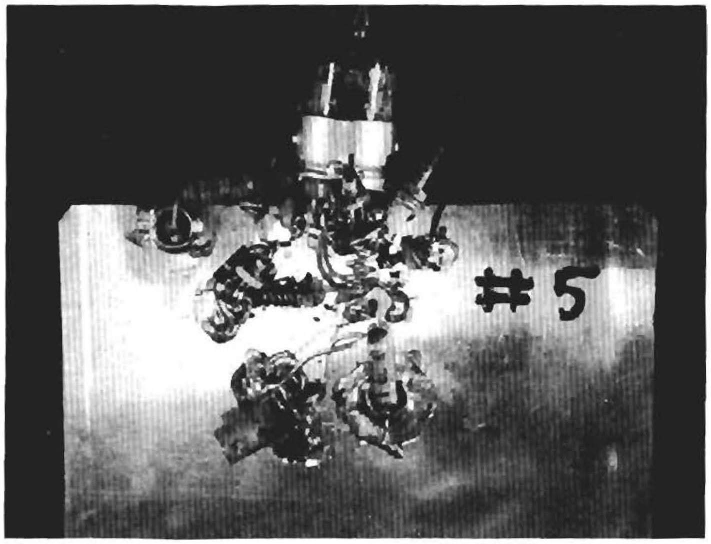


Figure 18. The 200- to 300-Mc/Sec Modified Grounded-Grid Oscillator

oscillator is a tuned-plate tuned-grid oscillator with the cathode returned through a compensated crystal. The circuit diagram is shown in Figure 19. Except at crystal overtone frequencies, the cathode impedance is sufficiently high to prevent oscillations from occurring. With the triode vacuum tube, the plate-to-grid capacitance is sufficient to maintain oscillations, even with relatively high impedances in the cathode circuit. No coupling between the plate and grid inductances is required.

A model of this oscillator was constructed on the frame of a Mallory Inductuner with two of the Inductuner sections serving as plate and grid circuit elements. A photograph of the oscillator is shown in Figure 20. The crystal was compensated in the usual manner by placing an inductance across the crystal socket.

The first model of this oscillator to be constructed oscillated at 250 mc/sec with crystal 6 and with a stability which appeared to be better than that of any of the other oscillators described for the frequency range above

ALL CAPACITANCE VALUES IN MICROMICROFARADS.
ALL RESISTANCE VALUES IN OHMS.
K = 1000

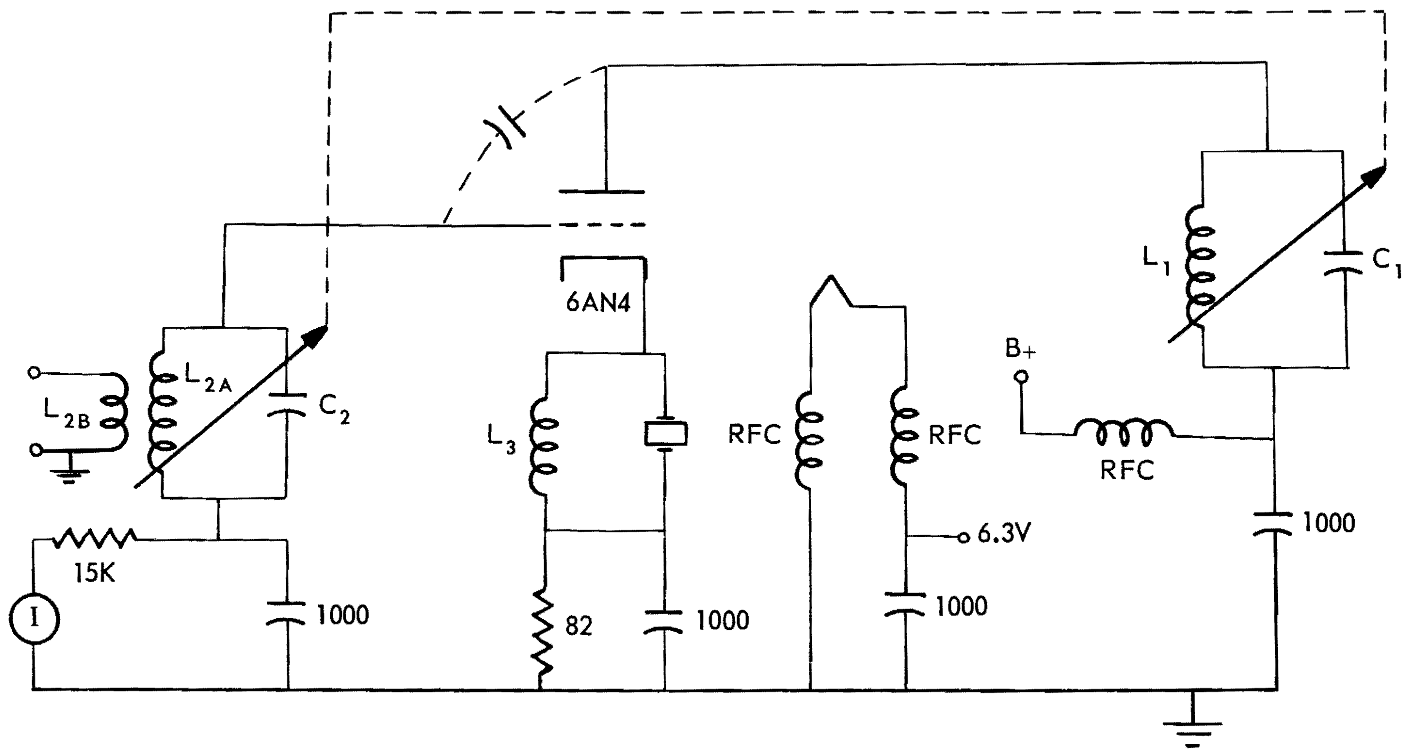


Figure 19. The Cathode-Degenerative Oscillator Circuit Diagram.

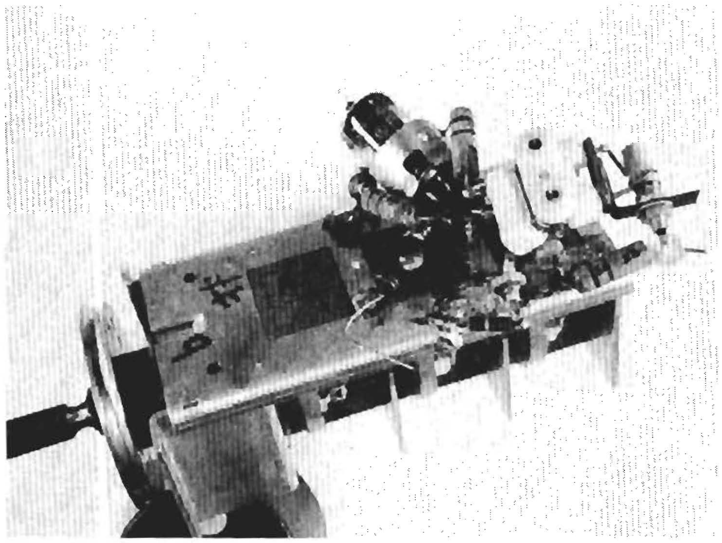


Figure 20. The 200- to 250-Mc/Sec Cathode-Degenerative Oscillator

200 mc/sec. Oscillation over a wide range of frequencies was possible when the crystal socket was replaced by a Y-yoke crystal socket so that both the crystal and the compensating inductor could be chosen. With this arrangement, crystal-controlled oscillations were obtained from 200 to 250 mc/sec. Crystal control at higher frequencies was not obtained because of the excessive lengths of leads to the Y-yoke socket.

Squegging was observed with this oscillator on several occasions. A suitable choice of crystal compensating inductor eliminated the squegging in every case. By trial and error, the correct inductors were chosen for several individual crystals. Table I shows the minimum and maximum resistance values of several crystals which provided crystal control.

The typical oscillator instability with the crystals of Table I was ±10 cycles per second for a period of 30 seconds. Supply voltage variations of 10 percent produced frequency variations from 500 to 2000 cycles per second.

A second model of the cathode-degenerative oscillator was constructed to obtain crystal control at higher frequencies. Particular care was given to

TABLE I

CRYSTALS FOR USE WITH THE FIRST CATHODE-DEGENERATIVE OSCILLATOR

Crystal	Frequency (Mc/Sec)	R_{min} (Ohms)	R_{max} (Ohms)
6	250	110	500
5	250	130	600
FA-117	245	50	600
MA-23	242	180	650
FA-105	231	55	500
FA-89	217	59	1000

the cathode circuitry to maintain minimum lead lengths. Provisions were made for soldering the crystal compensation inductor into the circuit. A conventional crystal socket was used, however, for mounting the crystal. With this oscillator, crystal control was obtained at frequencies as high as 290 mc/sec with stabilities comparable to those previously obtained. Table II lists the characteristics of the crystals used with this oscillator.

TABLE II

CRYSTALS FOR USE WITH THE SECOND CATHODE-DEGENERATIVE OSCILLATOR

Crystal	Frequency (Mc/Sec)	R_{min} (Ohms)	R_{max} (Ohms)
2W	275	68	500
5	283	104	400
6	283	82	360
FA-117	245	50	600
FA-40	252	110	300
FA-89	279	50	250

The oscillator frequency, with crystal 2W, changed less than ±10 cycles per second for one period of 8 minutes. A 10-percent supply voltage change, with crystal 2W, produced an 1800-cycles-per-second frequency change. The approximate temperature coefficient of this oscillator and crystal combination was 250 cycles per second per degree Centigrade.

The second cathode-degenerative oscillator was also operated at lower frequencies. One crystal compensation inductor provided crystal control with all of the crystals listed in Table III. Typical short term instabilities were

TABLE III

LOW-FREQUENCY CRYSTALS FOR USE WITH THE SECOND CATHODE-DEGENERATIVE OSCILLATOR

Crystal	Frequency (Mc/Sec)	R_{min} (Ohms)	R_{max} (Ohms)
FA-59	202	59	550
FA-67	209	112	670
FA-89	217	59	1000
FA-105	230	55	500
2W	225	62	1000
3W	225	†	†
1-A	220	†	†
2-A	220	†	†
MA-39	217	#	#
MA-38	217	#	#

†Crystal resistance data have not yet been obtained with these crystals.

#These crystals had been disregarded during previous crystal measurement runs because of their very poor quality. The minimum resistance was so high (probably much greater than 500 ohms) that neither the Crystal Measurements Standard System nor the substitution system could provide data.

again ±10 cycles per second, even with the poorer crystals such as MA-38 and MA-39. A particular advantage of this oscillator unit was its ability to maintain crystal control with almost any crystal having a response between 200 and 290 mc/sec.

h. Limitations On Present Measurements. The types of measurements which could be made on the previously described oscillators were severely limited by the available facilities. All frequency measurements were made by visual observation of a Berkeley frequency meter. A more desirable frequency measurement procedure would have required an analog frequency-voltage converter and a recording voltmeter. Such equipment would have provided a more accurate record of frequency variations with imposed conditions.

Data on frequency variations with temperature could be obtained only on rare occasions when the laboratory temperature was high and the outside ambient temperature was low. On one such occasion (with crystal 2W) a temperature change of 10°C was possible by forced ventilation. At the present time of the year, the laboratory and outside temperatures are approximately the same.

The frequency-temperature characteristics of the test crystals have not yet been determined; thus, the cause of oscillator frequency variations with temperature cannot presently be predicted.

Provisions for measuring crystal power dissipation have not been completed. A probe has been constructed, but a special connector for adapting it to an indicating instrument has not been procured.

When the facilities for measurements have been completed, the oscillators which have been described can be further tested to provide comparison data.

C. Phase III. Aging of Quartz Resonators

1. Introduction

This phase of the work, assigned the Project No. A-402-13 by the Engineering Experiment Station of the Georgia Institute of Technology, was initiated on 1 March 1959 and is a continuation of the work prior to that date under Contract No. DA-36-039 SC-78910, Georgia Tech Project No. A-402-3. The work undertaken on 1 March 1959 under the current contract, was subsequently expanded under Modification No. 1 to the Contract and renewed for an additional period of 12 months starting 1 July 1959 under Modification No. 4. This report, for the period 1 January 1960 to 31 March 1960, represents a continuation of the work described in the Interim Report and the preceding Quarterly Reports of the current contract.

The fabrication and measurement of 16.5-mc resonators operated in the fundamental mode, have been continued. The rate of effort on the 100-mc program has been reduced to a stand-by basis pending further financial provisions by the sponsor.

2. Apparatus and Procedures

No new apparatus was constructed during the quarter. Only minor apparatus changes and necessary maintenance work were carried out.

A new technique of sealing resonators in glass containers was investigated. A mounted unit is displayed in Figure 21. Spring clips were mounted on pins 2 and 7 of the small seven-pin radio-tube base and the plated resonator was mounted in the normal manner. The base was then sealed to a T-5-1/2 tubulated envelope with an epoxy resin, Bondmaster No. 640.

Figure 21. Resonator Mounted on Seven-Pin Base Sealed to Glass Envelope by Epoxy Resin Bondmaster No. 640.

The Bondmaster No. 640 epoxy resin is furnished in powder form. Application is made by melting it and flowing it on to surfaces to be joined. The T-5-1/2 bulbs were first sawed to length, and then 1/4 inch of the lip of the bulb was etched with ammonium bifluoride solution to afford good mechanical bonding. The bulb and base were joined by melting and flowing on the epoxy with a small Ungar soldering iron operated at 75 volts.

Since the epoxy softens during curing, a jig was constructed to clamp the parts together. Units so joined were cured in two groups. The first group was cured for 17 hours at 130°C. The second group was cured 4 hours at 150°C. No difference in appearance of the bond was observed as a result of the two curing methods.

The first group was vacuum baked 3 hours at 180°C before sealing off. The second group was vacuum baked 4 hours at 150°C before the final seal. The epoxy bonds of the group vacuum baked at the higher temperature changed color and became brittle. The bonds of the group baked at the lower temperature did not suffer this damage in appearance and the resin remained hard and tough. The sealing procedure should incorporate only the lower temperature suggested for bakeout.

3. Resonator Fabrication and Measurement

a. Resonators Fabricated During the Quarter. During the period of this report, the 49 resonators listed in Table IV have been fabricated and inserted in the constant temperature ovens at 85°C for frequency measurement.

These units were fabricated (a) to complete the study of aluminum base-plated units overcoated with a second selected metal and (b) to verify the behavior of other single metal films, with the use of the techniques of the

TABLE IV

RESONATORS FABRICATED AND MEASURED DURING QUARTER

Unit Designation	Number of Units Operated	Coating and Overcoating	Number of Units of Superior Stability
11-1 to 11-18	16	Al + Ag	5
12-1 to 12-9	8	Al + Cr	0 (-6ppm 60 days)
13-1 to 13-6	6	Evaporated Cu only	5
14-1 to 14-5	4	Sputtered Au only	4
15-1 to 15-7	7	Sputtered Ag only	6
16-1 to 16-10	8	Evaporated Au (Bondmaster seal)	4

more refined fabricating and processing steps now available. Representative plots of data obtained are shown in Figures 22, 23, 24, 25, 26, and 27.

In Table IV the numbers of units of superior stability are shown in the fourth column. In general a superior unit is considered one which shows a drift not greater than 0.5 ppm during the test period(less than 90 days in all cases) and no erratic or sharp drift rate. It will be noted that:

(1) The resonators plated with Al + Cr had a sharp negative slope indicative of oxidation or gas-gettering action on the part of the chromium overlayer.

(2) About two-thirds of the resonators plated with Al + Ag were unstable. A part of this instability is believed due to the employment of Hanovia No. 13 silver cement for the first five resonators fabricated. The resonators bonded with it exhibited high

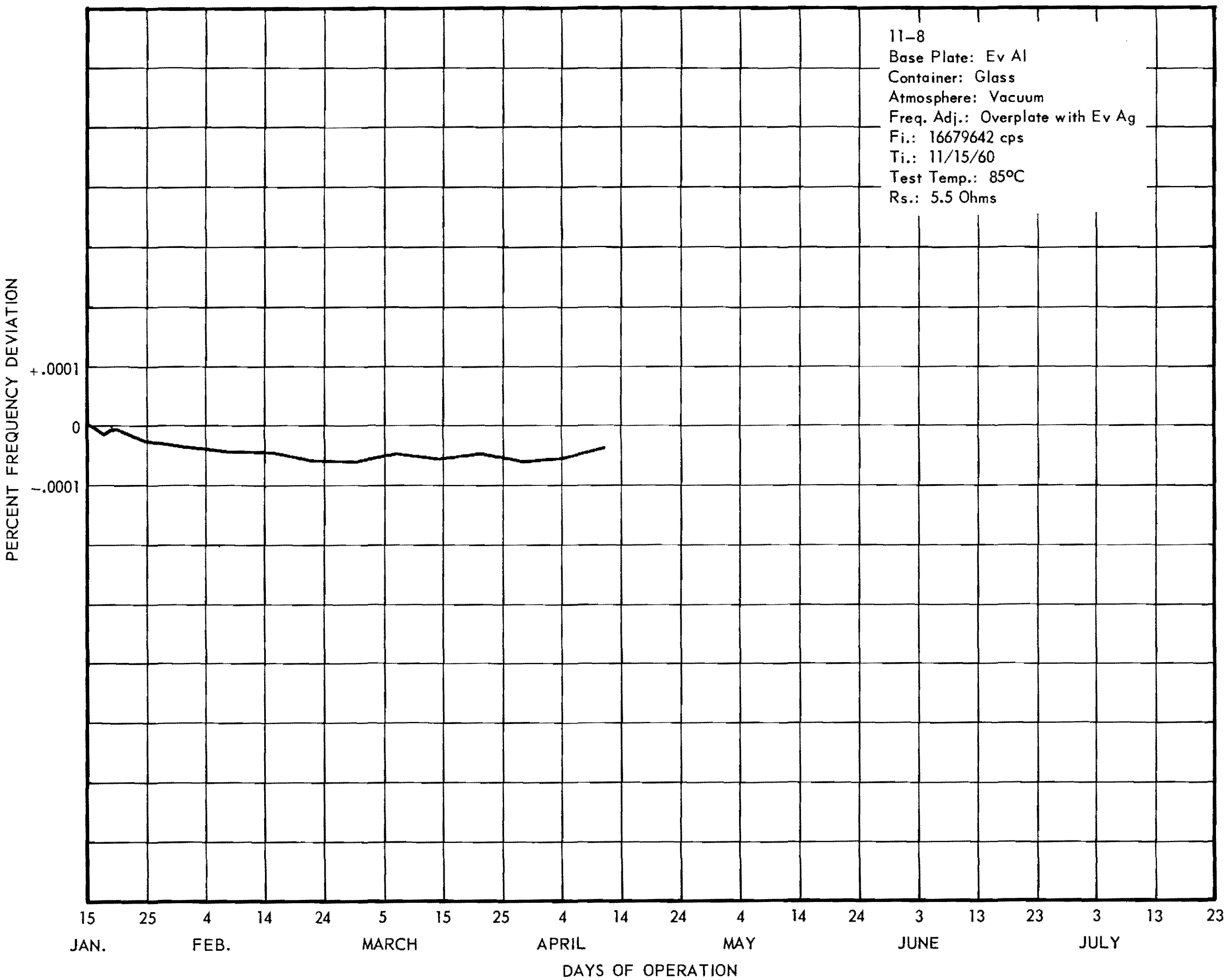


Figure 22. Plot of Frequency Versus Time for Resonator 11-8, Al + Ag.

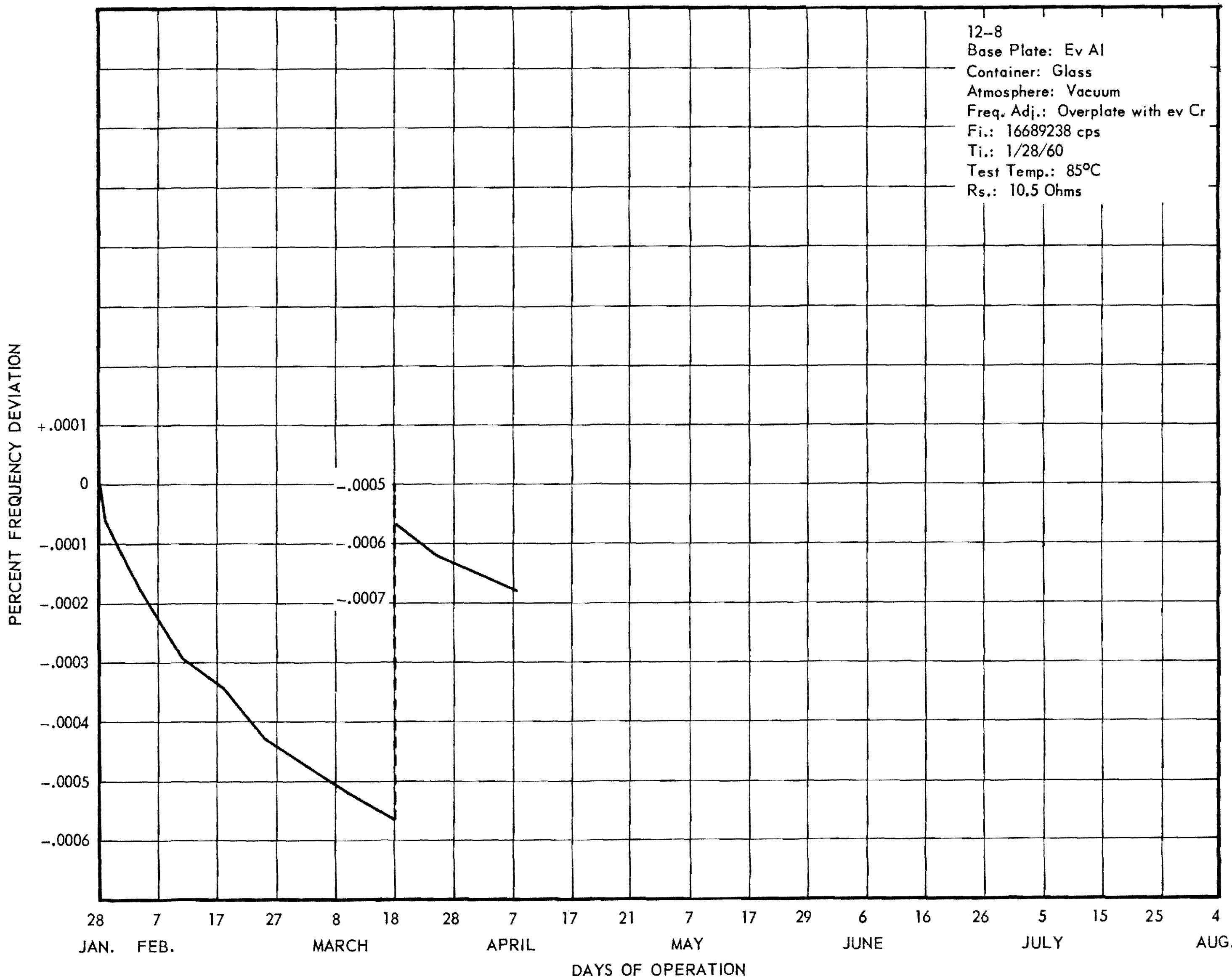


Figure 23. Plot of Frequency Versus Time for Resonator 12-8, Al + Cr.

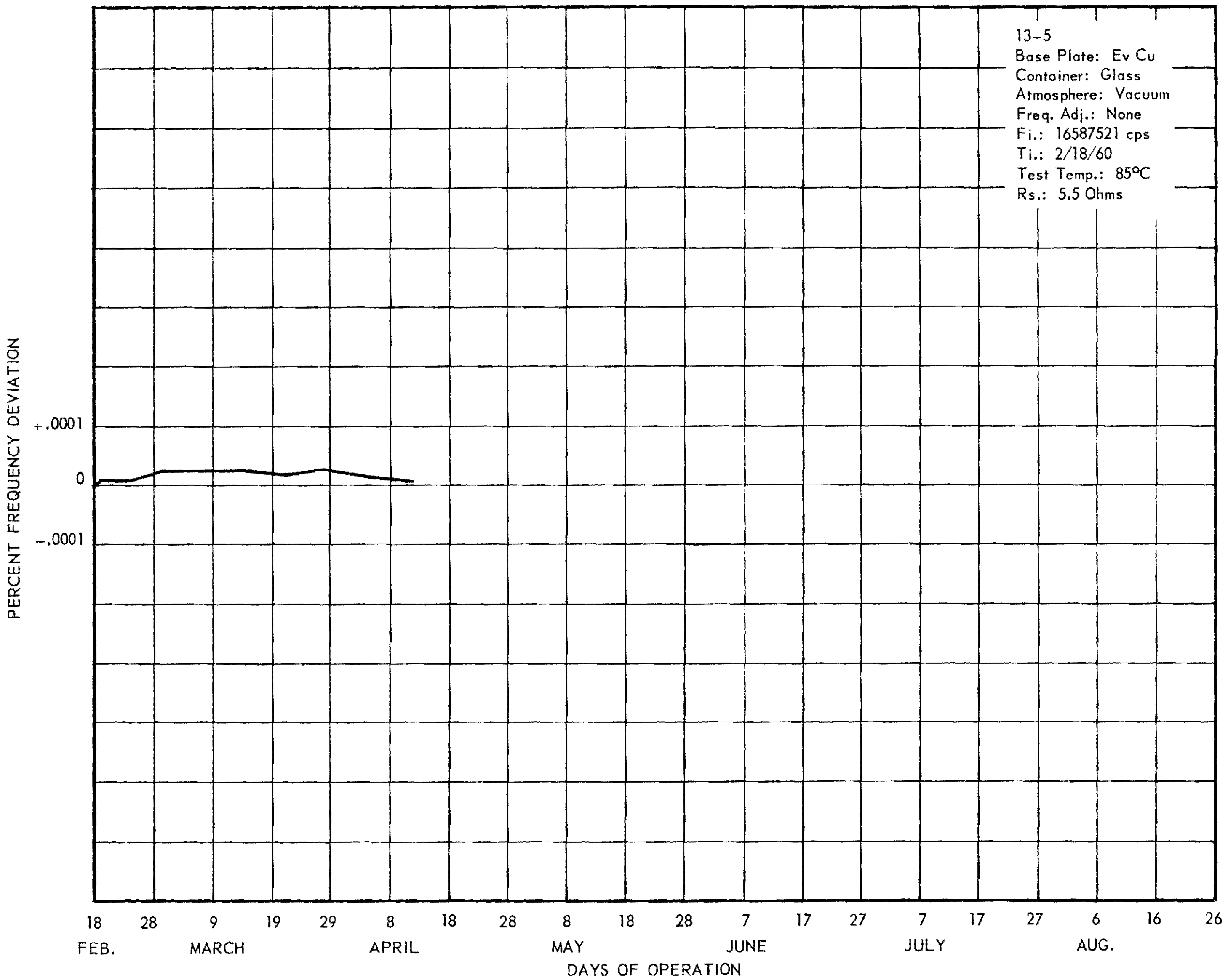


Figure 24. Plot of Frequency Versus Time for Resonator 13-5, Evaporated Only.

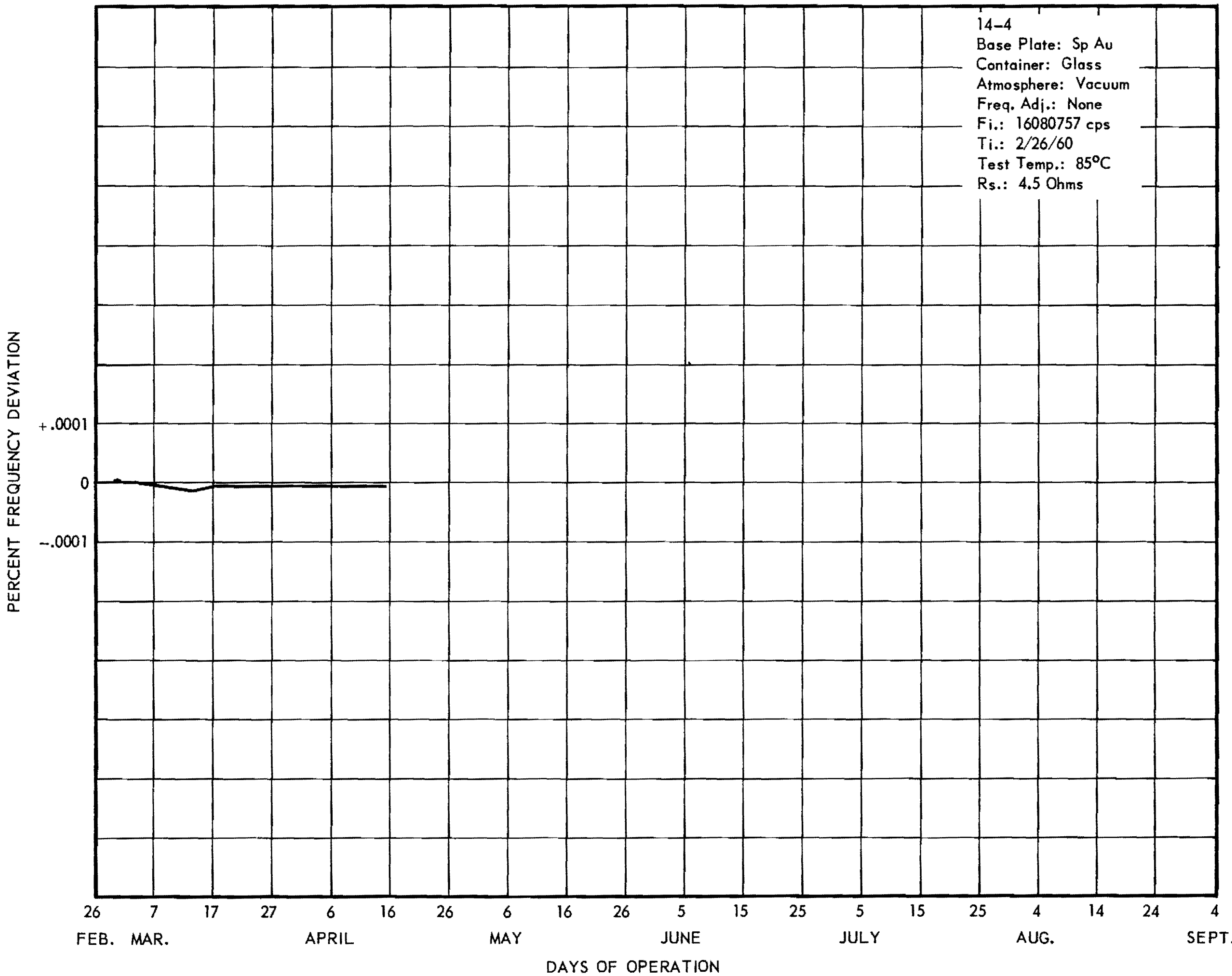


Figure 25. Plot of Frequency Versus Time for Resonator 14-4, Sputtered Only.

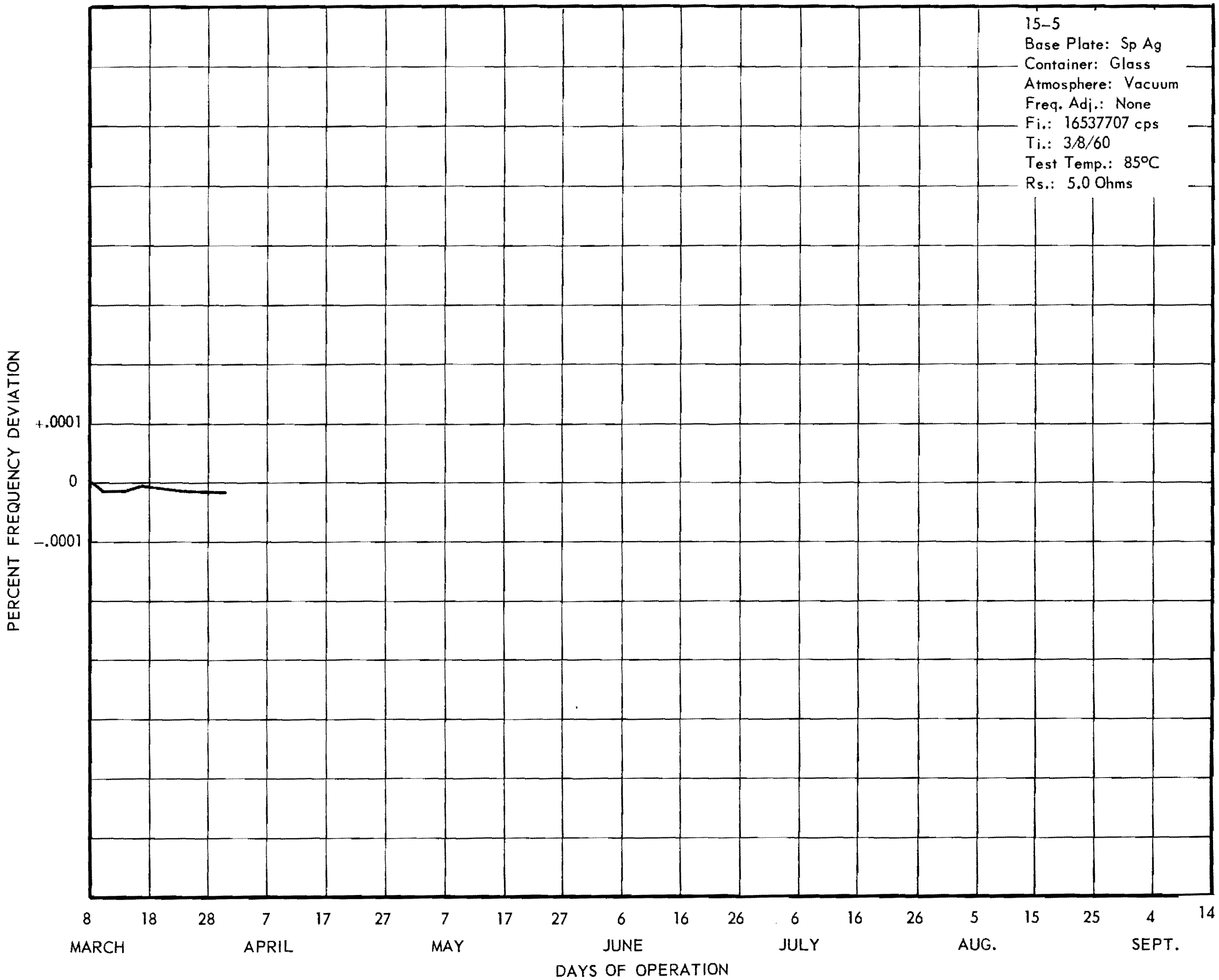


Figure 26. Plot of Frequency Versus Time for Resonator 15-5, Sputtered Only.

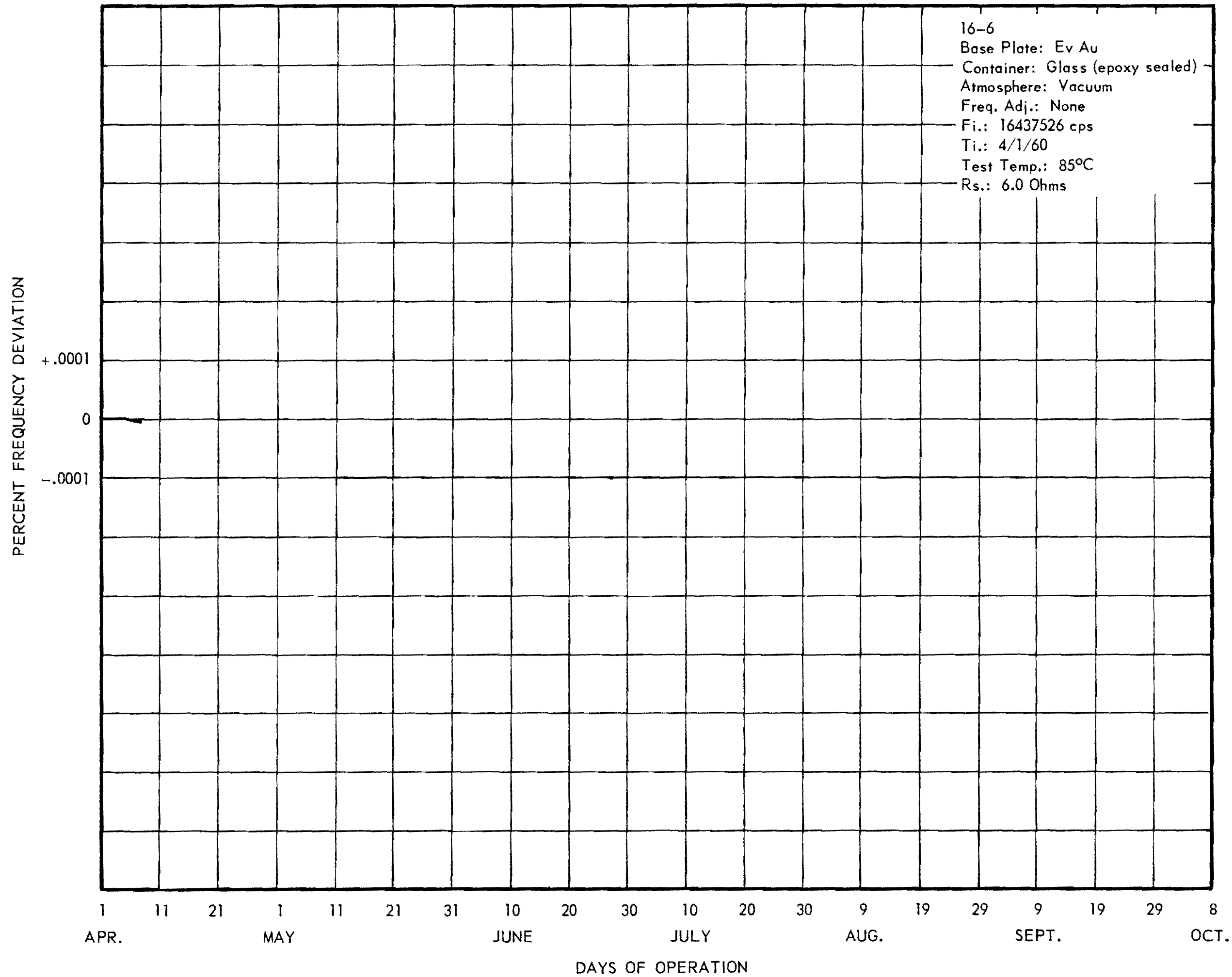


Figure 27. Plot of Frequency Versus Time for Resonator 16-6, Evaporated Bondmaster Seal.

R_s and some erraticity. A second reason suggested for the poor behavior of this group was that the silver wire evaporated over the aluminum was of poor appearance and may have been contaminated in some manner. Although Hanovia No. 2 cement was used for the remainder, a considerable degree of instability was exhibited by all units of the group.

(3) The resonators plated with copper only were surprisingly stable.

(4) The resonators plated with sputtered gold were very stable.

(5) The resonators plated with sputtered silver were fairly stable except for a slight positive shift.

(6) Four of the resonators with which Bondmaster No. 640 was used for sealing the base to the envelope were stable whereas four exhibited downward drifts, tentatively attributed to minute leaks. The stability of the four good ones was sufficient to indicate a need for further exploration of this sealing technique, which eliminates the drastic heating required for sealing glass to glass and allows shortened lead lengths to the resonator crystal. Short lead lengths will be a requirement for 100-mc operation.

b. Resonators Fabricated Previously and Continued on Measurement. Approximately 100 resonators previously fabricated have been continued on measurement during this quarter. Since these were discussed in detail during the last report, a further treatment of them, with the exception of one group, will be withheld until the Final Report.

Group 9, 14 units plated with Al + Al, is of particular interest. Ten of these units exhibited excellent stability whereas four behaved erratically.

These four were subsequently examined: two exhibited definite envelope cracks, hence leaks; one a cracked blank; and one appeared to have a very small leak as indicated by an examination with a discharge from a Tesla coil. Characteristic of the high stability obtainable with Al, even after overplating to frequency, is the plot of unit 9-9 displayed in Figure 28.

4. Summary

The fabrication and measurement of 49 additional resonators with the bimetal layers Al + Ag, and Al + Cr, and the single metals evaporated copper, sputtered gold, and sputtered silver as electrodes, have supported previous data to the effect that highly stable resonators can be produced with a wide choice of plating materials as long as cleanliness is observed in every detail of fabrication and the resonators are properly sealed. On the other hand, the coating Al + Cr gave resonators with a definite downward drift ascribed to the oxidation or gas adsorption of the chromium film. High R_s values were also exhibited by the resonators; hence this metal pair is obviously unsuitable for coating resonators.

The employment of a new fabrication technique for sealing the glass envelope to a seven-pin base gave a resonator of short lead lengths and did not expose the resonator to high temperatures during the sealing phase. Four of eight units exhibited excellent stability but four appeared to be leaking. If 90 to 100 percent certainty in sealing can be attained, this new technique will have many advantages for use with 100-mc resonators.

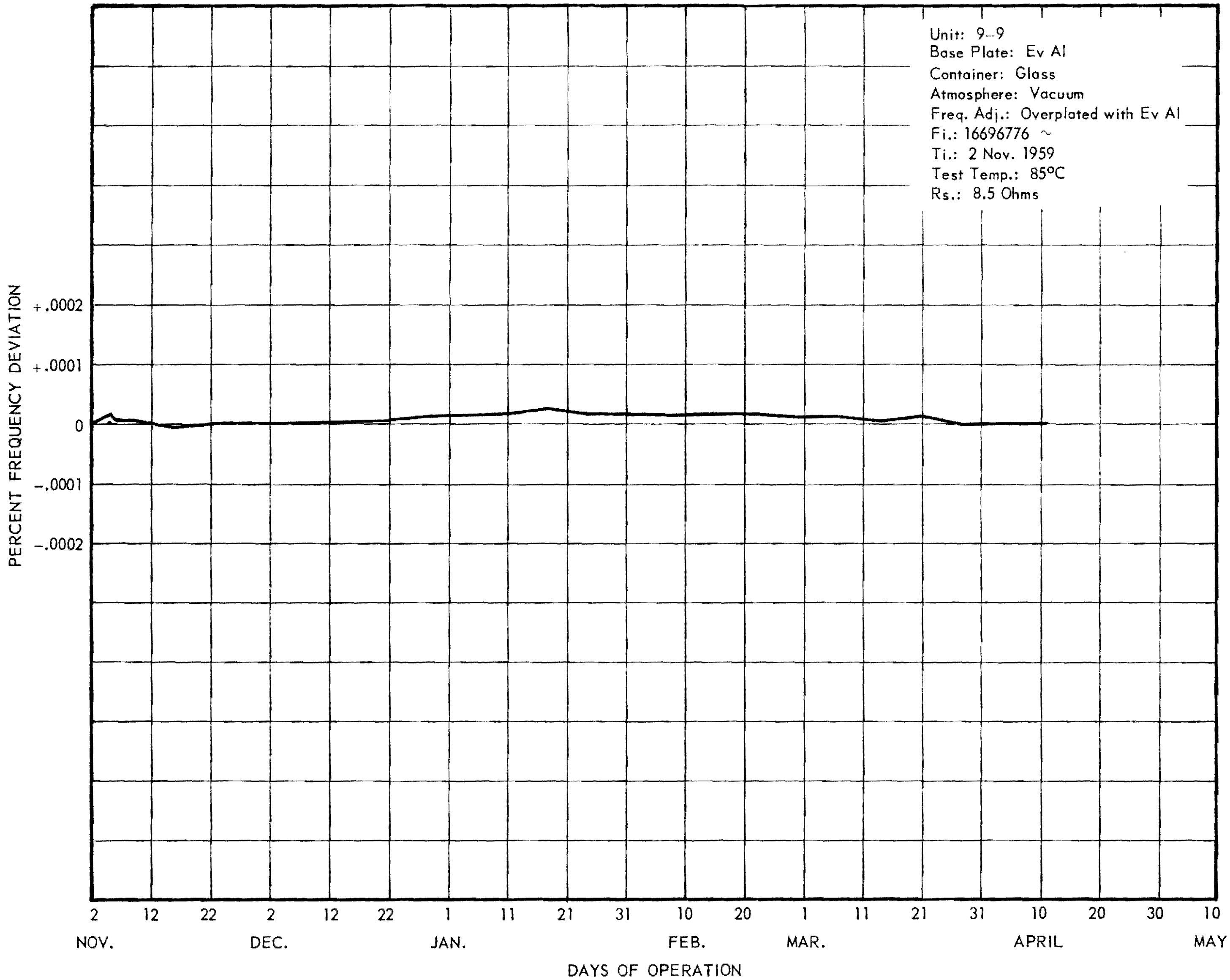


Figure 28. Plot of Frequency Versus Time for Resonator 9-9, Al + Al.

V. CONCLUSIONS

Under Phase I, the dimensional reduction of crystal D-1 was discontinued after a total of 147 steps averaging about 7 mm per step. No new modes of vibration were identified.

A series of fundamental frequency measurements on special circular and rectangular unbeveled crystals was initiated. The large number of spurious responses interfered with the spectrum and polarization measurements, even at the fundamental response. The unbeveled crystals were replaced by circular beveled plates of the same frequency (3 mc/sec). Preliminary measurements on these plates indicate that the desired data on the fundamental response can be obtained by suitable modification of the equipment.

Under Phase II, this period was devoted to the construction and testing of high-frequency crystal oscillators. Oscillators have been constructed which provide short term instabilities of less than ±10 cycles per second with supply voltage (but not temperature) regulation. Satisfactory crystal control with very poor crystals has been found possible at frequencies as high as 300 mc/sec.

Additional equipment must be procured and some existing equipment modified before oscillator evaluations can be completed. In particular, methods of temperature control and methods of continuously recording frequency variations are needed.

Under Phase III, the bimetal layer Al + Cr forms an unsatisfactory plating for quartz resonators.

Evaporated copper, sputtered gold and sputtered silver form satisfactory platings for quartz resonators when proper plating and mounting procedures are followed.

The feasibility of sealing a seven-pin base to a tubulated glass envelope with an epoxy resin such as Bondmaster No. 640, mounting therein a quartz resonator in the usual manner, and subsequently baking the unit in vacuo at about 150°C before the normal flame tip off, warrants further study. This sealing technique offers a possible method of eliminating high temperature during mounting and sealing 100-mc resonators in glass envelopes or in miniaturized containers.

VI. PROGRAM FOR THE NEXT INTERVAL

Under Phase I, the measurement of charge distribution for the fundamental mode of the beveled 3-mc/sec circular crystal will be completed and a paper prepared for the Frequency Control Symposium. The studies of the rectangular crystal at the third overtone frequency will then be resumed. A new mode chart will be prepared in which the amplitude of each response will be indicated by the size of the dot on the chart.

Under Phase II, the construction and testing of oscillator circuits will be continued. Plans for the necessary measurement equipment modifications and additions will be made and construction and/or procurement will proceed as funds permit.

Under Phase III, studies of fabrication materials and techniques for mounting of 16.5-mc/sec resonators will be continued. Included will be stability studies of aluminum-plated resonators mounted both in the HC-6/U can and in glass containers enclosing a getter material, and also resonators mounted in glass containers, the bases of which are sealed to the envelope with epoxies or related resins.

VII. IDENTIFICATION OF KEY TECHNICAL PERSONNEL

Under Phase I, no changes in project personnel have occurred during this report period. The personnel time is as follows:

NAME	TITLE	HOURS
Yasuo Tsuzuki	Assistant Research Engineer	480
S. N. Witt, Jr.	Assistant Project Director Research Engineer	70

Under Phase II, no changes in project personnel have occurred during this report period. The personnel time is as follows:

NAME	TITLE	HOURS
S. N. Witt, Jr.	Project Director Research Engineer	240
V. K. Woodcox	Research Assistant	480

Under Phase III, one change in project personnel occurred during this report period. Mr. J. C. Meaders, Research Assistant, was assigned to another project. Personnel time is as follows:

NAME	TITLE	HOURS
R. B. Belser	Project Director Research Associate Professor	120
W. H. Hicklin	Assistant Research Engineer	480
J. C. Meaders	Research Assistant	120
W. D. Dawson	Student Assistant	200

Respectfully submitted:

Samuel N. Witt, Jr.
Assistant Project Director
for Issac Koga, Project
Director, Phase I

Samuel N. Witt, Jr.
Project Director, Phase II

Richard B. Belser
Project Director, Phase III

Approved:

Arthur L. Bennett, Chief
Physical Sciences Division

VIII. BIBLIOGRAPHY TO PHASE II

References to particular oscillator circuits described in Chapter IV are as follows:

1. Gruen, H. E. and Plait, A. O., A Study of Crystal Oscillator Circuits. Final Report, Contract No. DA-36-039 SC-64609, Armour Research Foundation of Illinois Institute of Technology, Chicago, 14 August 1957.

2. Robertson, D. W. and Witt, S. N., Jr., Investigation of Methods for Measuring the Equivalent Electrical Parameters of Quartz Crystals. Progress Report No. 1, Contract No. DA-36-039 SC-71191, Engineering Experiment Station of the Georgia Institute of Technology, Atlanta, 15 July 1956.

3. Robertson, D. W., Witt, S. N., Jr., and Free, W. R., Investigation of Methods for Measuring the Equivalent Electrical Parameters of Quartz Crystals. Progress Report No. 2, Contract No. DA-36-039 SC-71191, Engineering Experiment Station of the Georgia Institute of Technology, Atlanta, 15 October 1956.

Another reference which was found to be particularly useful in the general design of oscillator circuits was:

Edson, W. A., Vacuum-Tube Oscillators. John Wiley and Sons, Inc., New York, 1953.

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FINAL REPORT

PROJECTS NO. A-402-11, -12, and -13

QUARTZ CRYSTAL STUDIES AND MEASUREMENTS

PHASE I. MOTIONAL PARAMETERS

By

ISSAC KOGA, YASUO TSUZUKI, and S. N. WITT, JR.

PHASE II. EQUIVALENT ELECTRICAL PARAMETERS

By

S. N. WITT, JR. and V. K. WOODCOX

PHASE III. AGING OF QUARTZ RESONATORS

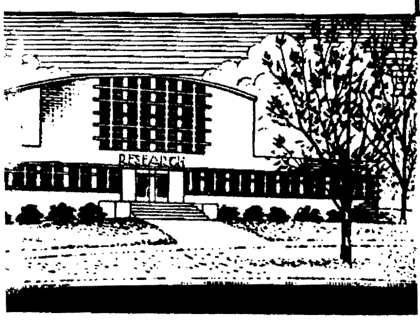
By

R. B. BELSER and W. H. HICKLIN

CONTRACT NO. DA-36-039 SC-78905

1 MARCH 1959 to 30 JUNE 1960

PLACED BY THE U. S. ARMY
SIGNAL RESEARCH AND DEVELOPMENT LABORATORIES
FORT MONMOUTH, NEW JERSEY



Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia

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Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia
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Final Report, 1 March 1959 to 30 June 1960, 235 pp. 130 Illus. Signal Corps Contract No. DA-36-039 SC-78905, Unclassified Report.

Under Phase I, the investigation of the modes of vibration of quartz crystals was continued. Three circular quartz blanks with sensibly identical spectral responses were studied over the diameter range from 23 mm to 18 mm in the vicinity of 3 mc/sec, the fundamental frequency. Mode charts and charge distribution models of specific modes were constructed. With the theoretical and experimental work on rectangular crystals previously completed in Japan as a guide, substantial progress was made in the interpretation of the much more complicated vibration patterns of the circular crystal.

The modes of the circular crystal corresponding to the inharmonic thickness-shear modes (1,1,0), (3,1,0), to (7,1,0) of the rectangular crystal at frequencies above the fundamental shear-mode frequency were traced as the diameter was reduced. The equivalent dimensions of a rectangular crystal were found to be 0.89 in x and 0.92 in z for the prediction of the frequency of the inharmonic overtones. Below the frequency of the fundamental thickness-shear mode two groups of vibrations were identified. The first is probably a group of face-shear vibrations with frequency nearly inversely proportional to diameter. The second more numerous group shows a frequency decrease with diameter suggestive of the flexural modes of the rectangular crystal.

Beveled circular crystal plates and triangular crystal plates were examined. The spectra, polarization patterns, and other considerations indicated that the behavior of these crystals cannot be fully explained until the simpler rectangular crystals have been further analyzed.

Analysis of the modes of vibration of a rectangular crystal in the vicinity of the third overtone, 3 mc/sec, was initiated. Expanded spectra covering the frequency range ±35 kc permit a detailed study of this region as well as the range ±400 kc also recorded. Measurements were completed and separate mode charts for strong and weak responses were plotted for the change in x_o dimension from 24.56 mm to 23.55 mm. Modes of four types, thickness-shear, flexure, and face shear in two directions, have been identified from the mode charts and confirmed by polarization measurements. The measured frequencies for the third harmonic overtone

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and for the face-shear modes are in good agreement with values calculated from the recent work by Koga, et al.

Techniques are described for the measurement of the charge distribution on the surface of a crystal with electrodes covering only a portion of the surface. The charge distribution with a full electrode and with a 9.5-mm electrode is shown to be symmetrical for a beveled circular crystal only when the surfaces are polished plane-parallel.

Under Phase II, a substitution measurement system for determining the more important parameters of high-frequency quartz crystals was developed. With the exception of crystal Q, the parameters may be determined very rapidly and with a precision sufficient for most applications. The determination of crystal Q requires some mathematical calculations. The system has given useful information at frequencies as high as 400 mc/sec.

The substitution measurement system was used in the studies of crystal drive level effects and also for the determination of crystal temperature coefficients. Detailed information on the effects of temperature, for use in the oscillator design program, was obtained for several crystals.

Six months of the contract period were devoted to the design and testing of high-frequency oscillator circuits. Both vacuum-tube and transistor circuits were studied. Typical instabilities of less than ± 10 cycles per second for short periods of time were obtainable with vacuum-tube oscillators over the frequency range from 150 to 300 mc/sec. Several transistorized crystal-controlled oscillators were constructed for frequencies up to 300 mc/sec. Typical short-term instabilities were an order of magnitude less than for similar vacuum-tube oscillators. Longer-term stabilities of the transistorized oscillators were superior because of the reduced crystal heating; the power dissipation of typical transistorized circuits was 6 mw compared to about 4 watts for the vacuum-tube units. Some other oscillator characteristics were measured; however, the facilities for the full evaluation of oscillator units have not yet been completed.

Under Phase III, bridge measurement system for 100-mc AT-cut quartz resonators was devised. Ovens for storage of units at 0° and 60°C and for cycling between these temperatures were partially constructed. One group of six aluminum-coated 100-mc resonators was fabricated and measured. Over 150 aluminum-plated AT-cut quartz resonators of 16.5-mc fundamental frequency were mounted and sealed in glass or metal containers. The better units, stored at 85°C, maintained drift rates of < 1 ppm per year. Although high stabilities were more frequently displayed by units which were only base plated, units overcoated to frequency with a second coat performed only slightly less well. Aluminum, silver, gold, and copper were utilized as the overcoating materials and all were found to be satisfactory provided an aluminum oxide interface existed between the aluminum and any different metal used as the overcoat. Units mounted in glass containers were usually superior in performance to those in metal containers but stabilities as good as those in glass were obtained by some units in metal containers.

Resonators coated with sputtered gold, sputtered silver, or with evaporated copper proved of excellent stability as well. Gold-coated resonators, in a glass envelope in which a getter was flashed subsequent to sealing, displayed positive drifts of 3 to 5 ppm in 60 days but gave promise of reaching a stable frequency plateau within 120 days of the fabrication date. Vacuum oil leak tests of 569 industrially fabricated 16.25-mc resonators indicated 83 percent leakers and pointed again to generally poor hermetic sealing with the current HC-6/U container. A part of this is ascribable to lack of proper procedures in sealing, but a major contributing factor is the currently used sintered glass base which has intrinsic mechanical weakness and appears to be a source of undesirable outgassing.

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Final Report, 1 March 1959 to 30 June 1960, 235 pp. 130 Illus. Signal Corps Contract No. DA-36-039 SC-78905, Unclassified Report.

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The modes of the circular crystal corresponding to the inharmonic thickness-shear modes (1,1,0), (3,1,0), to (7,1,0) of the rectangular crystal at frequencies above the fundamental shear-mode frequency were traced as the diameter was reduced. The equivalent dimensions of a rectangular crystal were found to be 0.89 in x and 0.92 in z for the prediction of the frequency of the inharmonic overtones. Below the frequency of the fundamental thickness-shear mode two groups of vibrations were identified. The first is probably a group of face-shear vibrations with frequency nearly inversely proportional to diameter. The second more numerous group shows a frequency decrease with diameter suggestive of the flexural modes of the rectangular crystal.

Beveled circular crystal plates and triangular crystal plates were examined. The spectra, polarization patterns, and other considerations indicated that the behavior of these crystals cannot be fully explained until the simpler rectangular crystals have been further analyzed.

Analysis of the modes of vibration of a rectangular crystal in the vicinity of the third overtone, 3 mc/sec, was initiated. Expanded spectra covering the frequency range ±35 kc permit a detailed study of this region as well as the range ±400 kc also recorded. Measurements were completed and separate mode charts for strong and weak responses were plotted for the change in x_o dimension from 24.56 mm to 23.55 mm. Modes of four types, thickness-shear, flexure, and face shear in two directions, have been identified from the mode charts and confirmed by polarization measurements. The measured frequencies for the third harmonic overtone

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Resonators coated with sputtered gold, sputtered silver, or with evaporated copper proved of excellent stability as well. Gold-coated resonators, in a glass envelope in which a getter was flashed subsequent to sealing, displayed positive drifts of 3 to 5 ppm in 60 days but gave promise of reaching a stable frequency plateau within 120 days of the fabrication date. Vacuum oil leak tests of 569 industrially fabricated 16.25-mc resonators indicated 83 percent leakers and pointed again to generally poor hermetic sealing with the current HC-6/U container. A part of this is ascribable to lack of proper procedures in sealing, but a major contributing factor is the currently used sintered glass base which has intrinsic mechanical weakness and appears to be a source of undesirable outgassing.

ENGINEERING EXPERIMENT STATION
of the Georgia Institute of Technology
Atlanta, Georgia

FINAL REPORT

PROJECTS NO. A-402-11, -12, and -13

QUARTZ CRYSTAL STUDIES AND MEASUREMENTS

PHASE I. MOTIONAL PARAMETERS

By

ISSAC KOGA, YASUO TSUZUKI, and S. N. WITT, JR.

PHASE II. EQUIVALENT ELECTRICAL PARAMETERS

By

S. N. WITT, JR. and V. K. WOODCOX

PHASE III. AGING OF QUARTZ RESONATORS

By

R. B. BELSER and W. H. HICKLIN

CONTRACT NO. DA-36-039 SC-78905

1 MARCH 1959 to 30 JUNE 1960

The object of this research is the enhancement of the understanding of the behavior of quartz crystals as frequency control and filter devices.

PLACED BY THE U. S. ARMY
SIGNAL RESEARCH AND DEVELOPMENT LABORATORIES
FORT MONMOUTH, NEW JERSEY

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I. PURPOSE

The purpose of this contract was to advance the state of the art of applications of quartz crystals as frequency control and filter elements. Investigations and studies were conducted simultaneously in three areas of specialization:

Phase I. Motional Parameters

Phase II. Equivalent Electrical Parameters

Phase III. Aging of Quartz Resonators

Phase I was concerned with the study of motional parameters of thickness-shear and contour-shear modes of vibration of crystal plates. The purpose of Phase I was fourfold:

1. To continue the measurements of frequency and strain distributions of thin circular discs;

2. To measure frequency and strain distributions of plates having a smaller diameter-thickness ratio and adequately beveled to eliminate couplings with other modes;

3. To measure frequency and strain distributions of some triangular plates of the AT-cut; and

4. To conduct investigations which are concerned with the measurement of parameters of the equivalent electric circuit of circular plates, particularly to determine the influence of the electrode diameter and the motional capacitance constant, Γ, on the motional parameters.

Phase II was concerned with methods and techniques for determining the equivalent electrical parameters of quartz crystal units. The purpose of Phase II was threefold:

1. To continue the investigation of applications of crystal units in VHF and UHF oscillators for frequencies above 175 mc/sec to determine the following:

(a) crystal parameters useful in oscillator circuit design,

(b) methods and techniques for determining crystal parameters, and

(c) test requirements for crystal units;

2. To design and construct experimental models of 175- to 300-mc/sec quartz crystal test sets capable of:

(a) testing crystal units employing HC-6/U and HC-18/U holders,

(b) determining the series resonant condition with a frequency accuracy of ±1 ppm,

(c) indicating directly the crystal power dissipation with an accuracy such that the resultant frequency accuracy is ±1 ppm, and

(d) operation with crystal power dissipation in the range 0.2 to 4.0 mw;

3. To perform studies and investigations leading to the development of methods and techniques for determining the equivalent parameters of crystal units in the frequency range of 300 to 500 mc/sec with emphasis on information pertinent to the eventual development of crystal specifications and crystal test sets.

Phase III was concerned with the effects of processing techniques and materials on aging of quartz crystal units. The purpose was threefold:

1. To fabricate experimental crystal units as follows:

(a) At-cut, fundamental mode, 16.0 mc/sec, gold and silver base plate, adjusted to frequency by evaporation or electrolysis of a second compatible metallic film, evacuated glass holders,

(b) AT-cut, third and fifth overtone modes, 48.0 and 80.0 mc/sec, evaporated aluminum base plate only, evacuated glass holders, and

(c) At-cut, third and fifth overtone modes, 48.0 and 80.0 mc/sec, evaporated aluminum base plate, adjusted to frequency with evaporated aluminum, evacuated glass holders;

2. To measure for 6 months the frequency and resistance of crystal units stored at approximately 25°, 85°, and 125°C;

3. To determine, from an analysis of the data, the degree of compatibility of the frequency adjustment metal with the base plate metal.

In addition to the above requirements any other problems pertinent to the three phases which arose during the course of the studies and which were mutually agreed upon between the contracting officer's technical representative and the contractor were investigated.

II. ABSTRACT

Under Phase I, the investigation of the modes of vibration of quartz crystals was continued. Three circular quartz blanks with sensibly identical spectral responses were studied over the diameter range from 23 mm to 18 mm in the vicinity of 3 mc/sec, the fundamental frequency. Mode charts and charge distribution models of specific modes were constructed. With the theoretical and experimental work on rectangular crystals previously completed in Japan as a guide, substantial progress was made in the interpretation of the much more complicated vibration patterns of the circular crystal.

The modes of the circular crystal corresponding to the inharmonic thickness-shear modes (1,1,0), (3,1,0), to (7,1,0) of the rectangular crystal at frequencies above the fundamental shear-mode frequency were traced as the diameter was reduced. The equivalent dimensions of a rectangular crystal were found to be 0.89 in x and 0.92 in z for the prediction of the frequency of the inharmonic overtones. Below the frequency of the fundamental thickness-shear mode two groups of vibrations were identified. The first is probably a group of face-shear vibrations with frequency nearly inversely proportional to diameter. The second more numerous group shows a frequency decrease with diameter suggestive of the flexural modes of the rectangular crystal.

Beveled circular crystal plates and triangular crystal plates were examined. The spectra, polarization patterns, and other considerations indicated that the behavior of these crystals cannot be fully explained until the simpler rectangular crystals have been further analyzed.

Analysis of the modes of vibration of a rectangular crystal in the vicinity of the third overtone, 3 mc/sec, was initiated. Expanded spectra covering the frequency range ± 35 kc permit a detailed study of this region as well as the

range ± 400 kc also recorded. Measurements were completed and separate mode charts for strong and weak responses were plotted for the change in x_o dimension from 24.56 mm to 23.55 mm. Modes of four types, thickness-shear, flexure, and face shear in two directions, have been identified from the mode charts and confirmed by polarization measurements. The measured frequencies for the third harmonic overtone and for the face-shear modes are in good agreement with values calculated from the recent work by Koga, et al.

Techniques are described for the measurement of the charge distribution on the surface of a crystal with electrodes covering only a portion of the surface. The charge distribution with a full electrode and with a 9.5-mm electrode is shown to be symmetrical for a beveled circular crystal only when the surfaces are polished plane-parallel.

Under Phase II, a substitution measurement system for determining the more important parameters of high-frequency quartz crystals was developed. With the exception of crystal Q, the parameters may be determined very rapidly and with a precision sufficient for most applications. The determination of crystal Q requires some mathematical calculations. The system has given usesul information at frequencies as high as 400 mc/sec.

The substitution measurement system was used in the studies of crystal drive level effects and also for the determination of crystal temperature coefficients. Detailed information on the effects of temperature, for use in the oscillator design program, was obtained for several crystals.

Six months of the contract period were devoted to the design and testing of high-frequency oscillator circuits. Both vacuum-tube and transistor circuits were studied. Typical instabilities of less thatn ±10 cycles per second for short periods of time were obtainable with vacuum-tube oscillators over the frequency range from 150 to 300 mc/sec.

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III. PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

One publication, "The Alloying Behavior of Thin Bimetal Films, Successively or Simultaneously Deposited" was published by Mr. R. B. Belser in the Journal of Applied Physics, Vol. 31, p. 562, March 1960. A large part of the work reported was done under Contract No. DA-36-039 SC-42453 of the Signal Corps during the years 1953 and 1954.

No lectures or reports, related to this contract, have been presented other than as required by the contract.

On 19 March 1959, Mr. R. B. Belser, representing Phase III, visited Bliley Electric Company at Erie, Pennsylvania, to discuss the fabrication of resonator units.

The Thirteenth Annual Symposium on Frequency Control was attended on 12, 13, and 14 May 1959 by Dr. Hitohiro Fukuyo, Dr. J. E. Rhodes, Mr. S. N. Witt, Jr., Mr. V. K. Woodcox, Mr. R. B. Belser, Mr. W. H. Hicklin and Dr. A. L. Bennett. The following papers were presented: "Modes of Vibration of Quartz Crystal Resonators Investigated by Means of the Probe Method" by I. Koga, H. Fukuyo, and J. E. Rhodes; "Methods for Measuring Quartz Crystal Units at VHF" by S. N. Witt, Jr.; and "Aging Studies on Crystal Units" by R. B. Belser and W. H. Hicklin.

A general conference to define the technical program of all three phases of the project was held at USASRDL on 3 September 1959. The following Georgia Tech persons attended: Dr. J. E. Rhodes, Jr., Dr. Issac Koga, Mr. Yasuo Tsuzuki, Mr. S. N. Witt, Jr., Mr. R. B. Belser and Dr. A. L. Bennett.

On 24 November 1959, Dr. G. K. Guttwein and Dr. R. Bechmann visited Georgia Tech. Progress on Phases I and III was reviewed. A decision to make spectra and polarization measurements on special 3-mc/sec crystals up to 28 mm in size was reached. The purpose of this addition to the program of Phase I was to investigate the behavior of circular electrodes of diameters from 3 to 21 mm.

On 21 January 1960, Mr. Dennis Pochmerski visited Georgia Tech to discuss progress and future plans on Phase II. A program for the construction and intercomparison of VHF and UHF crystal-controlled oscillators was agreed upon. It was decided that further work with the substitution measurement system would be discontinued.

On 4 February 1960, Mr. R. B. Belser attended a conference with Dr. G. K. Guttwein, Mr. P. E. Mulvihill, Mr. J. M. Stanley, and Mr. M. Bernstein of USASRDL. Discussions concerning a revised satellite resonator program were held. The need for an Atomichron frequency standard was outlined and its possible availability for the program was established. A proposal on the research discussed was submitted to USASRDL on or about 24 February 1960.

On 24 March 1960, Mr. S. N. Witt, Jr., visited USASRDL for conferences with Dr. G. K. Guttwein and Dr. R. Bechmann concerning Phase I. Measurements on special crystals, as currently reported, were discussed. An immediate program to measure the fundamental polarization responses and spectra of 3-mc/sec beveled circular crystal plates as a function of electrode diameter was agreed upon. It was further agreed that the measurements of the special circular and rectangular unbeveled plates would be discontinued because of the high number of spurious responses.

On 25 March 1960, Mr. S. N. Witt, Jr., and Mr. V. K. Woodcox visited USASRDL for conferences with Mr. O. P. Layden and Mr. D. Pochmerski concerning Phase II. The previously and currently reported crystal oscillator studies were discussed. It was agreed that the studies of vacuum-tube oscillator circuits should be continued and that initial studies of transistor and tunnel diode applications should be initiated. It was also agreed that lower-frequency (below 200 mc/sec) oscillator circuits should be constructed for comparison of frequency stability, harmonic content, output amplitude, and other characteristics, with the higher frequency oscillators. In particular, the lower frequency oscillators should include harmonic multipliers to provide output energy at the higher frequencies.

The Fourteenth Annual Symposium on Frequency Control was attended on 31 May and 1 and 2 June 1960 by Dr. Issac Koga, Mr. Yasuo Tsuzuki, Mr. R. B. Belser, Mr. S. N. Witt, Jr., Mr. V. K. Woodcox and Dr. A. L. Bennett. The following papers were presented: "Polarization Measurements of the Vibrations of Quartz Plates" by I. Koga, Y. Tsuzuki, S. N. Witt, Jr., and A. L. Bennett and "Aging Characteristics of Quartz Crystal Units" by R. B. Belser and W. H. Hicklin. Conferences were also held between various Georgia Tech personnel and USASRDL personnel concerning future activities of the respective phases of the contract.

IV. FACTUAL DATA

A. Phase I. Motional Parameters

1. Introduction

This phase of the work, assigned the Project No. A-402-11 by the Engineering Experiment Station of the Georgia Institute of Technology, was initiated on 1 March 1959 and was a continuation of the work prior to that date on Contract No. DA-36-039 SC-78910, Project A-402-1.

Under Contract No. DA-36-039 SC-78910, Dr. Fukuyo had begun an investigation of the spectra of circular AT-cut quartz crystal plates. This investigation was continued into the current contract and is described in section A.2. The equipment used in this investigation is not described here since it is very similar to that used by Mr. Tsuzuki as described later.

Dr. Fukuyo also briefly investigated the responses of beveled circular crystal plates and of triangular crystal plates as will be described in sections A.3. and A.4. These studies were to determine the feasibility of detailed analyses of these tyes of plates.

During August 1959, Dr. Fukuyo returned with his equipment to the Tokyo Institute of Technology. Before the departure of Dr. Fukuyo, Mr. Tsuzuki arrived with his equipment from the Yokahama National University. Mr. Tsuzuki's program consisted of measuring the spectra and charge distributions for rectangular crystal plates at a third overtone frequency of 3 mc/sec as described in section A.5. Continuation of Dr. Fukuyo's investigations of the circular and triangular plates was considered undesirable at that time because of the lack of detailed knowledge of the modes of vibration of even the simpler rectangular plates.

The third overtone investigations of the rectangular plates were not fully completed because a special investigation of responses of circular plates as a function of electrode diameters, described in section A.6., was requested by USASRDL.

2. Spectra and Modes of Vibration of Circular AT-Cut Quartz Crystals

a. Mode Chart Preparation. For these studies, a number of sensibly identical circular AT-cut quartz crystal blanks were obtained. All of the blanks were held to the dimensions and frequency tolerance here specified:

Angle of cut: 35° 15' ± 2'

Diameter: 25 mm ± 0.1 mm

Fundamental frequency: 3 mc ± 5 kc

Thickness determined by frequency: as delivered, $y_o = 0.557$ mm ± 0.001 mm

Similarity between blanks: diameter within ± 0.01 mm orientation within 2 minutes

Principal planes of each blank: parallel to within 0.001 mm

Polish: at least to a milky white surface or, if necessary, to an optical surface to obtain the required dimensions and tolerances

Temperature of operation: 25°C, ± 5°C.

The spectral response of each of these blanks was taken in the frequency range from 2.4 to 4.0 mc/sec. The spectral response of each of the crystals selected for this study was sensibly the same. The close similarity of spectral response along with the close dimensional tolerances served to classify all of these crystal blanks as identical.

One of the crystals was selected for the preparation of a mode chart. The diameter of this crystal was reduced a small amount and then its spectrum was again taken. This process was repeated as the diameter of the crystal was successively reduced in steps of approximately 1/16 mm. In each spectrum all responses stronger than a selected minimum were plotted on the mode chart with the crystal diameter as abscissa and the frequency of response as ordinate. These selected responses of the crystal in the ranges of frequency and diameter covered by this study are shown in the mode chart, Figure 1.

A similar procedure with the rectangular crystal had dropped out weak modes of vibration and left much stronger ones in which specific modes could readily be followed. Here, however, the multiplicity of responses and the lack of sharp distinction between principal modes and obscure ones gave few clues to be followed.

A new presentation was therefore devised, as shown in Figure 2. The strength of each response was estimated and this was indicated on the mode chart by the size of the mark. Now the strong responses stand out from the numerous weak ones and the trend of frequency with changing diameter has been traced.

Within the complexity of the mode chart of a circular crystal, several general features can be distinguished which are similar to the less complicated mode chart of a rectangular crystal, shown in Figure 3.† The mode charts both for the circular and for the rectangular crystal are clearly divided near the fundamental thickness-shear frequency into upper and lower parts. In the upper region of both the rectangular and circular mode charts there is a series of prominent responses that are not strongly dependent upon the abscissa but that are strongly coupled to a second series of responses. Responses of the second series are strongly dependent upon the abscissa. This second series of responses

†In the mode chart of the rectangular crystal the abscissa is the x-dimension of the rectangular AT-cut quartz crystal rather than the diameter of the circular crystal.

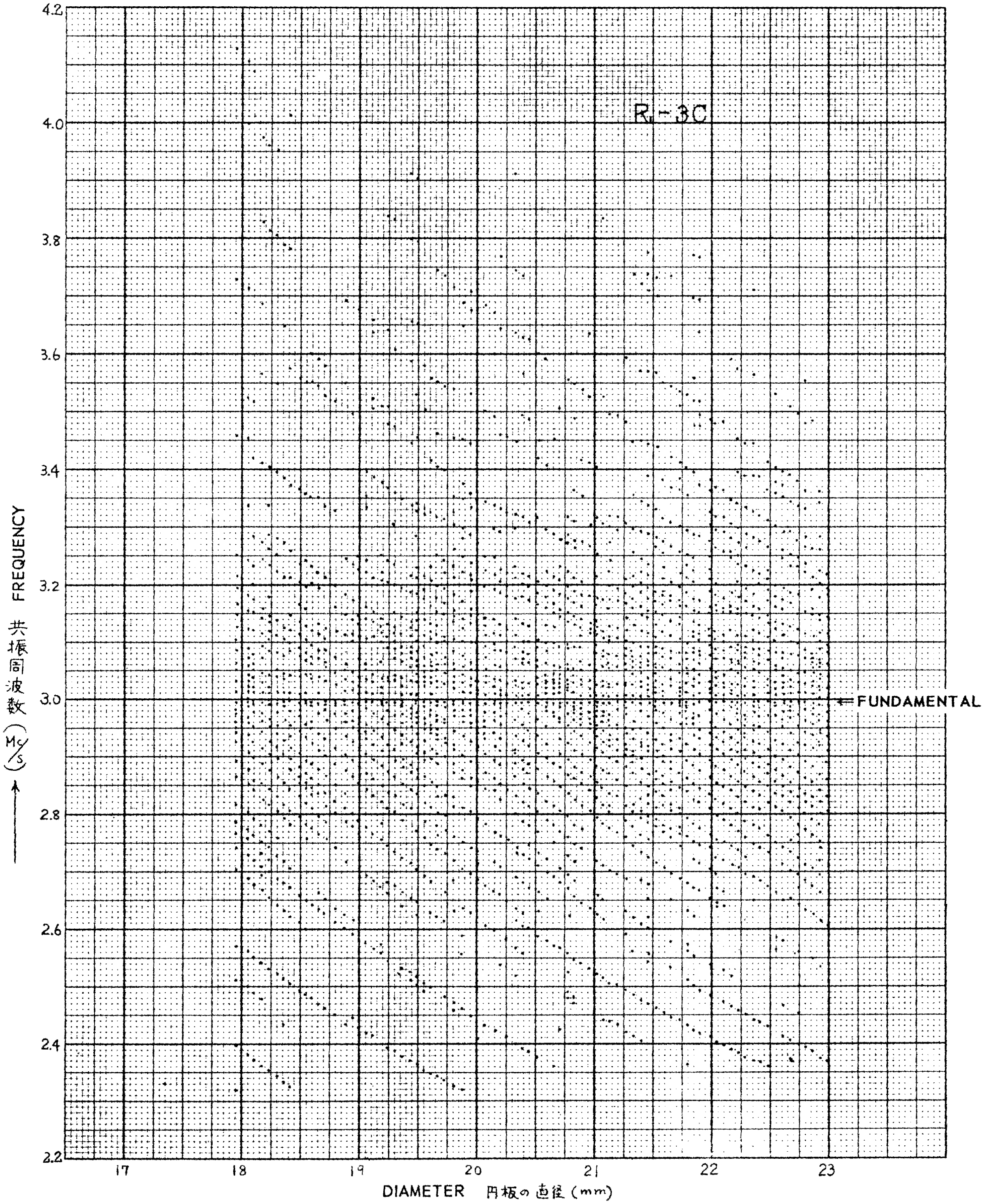


Figure 1. Mode Chart for a Circular Crystal Showing Only Responses Stronger Than a Selected Minimum.

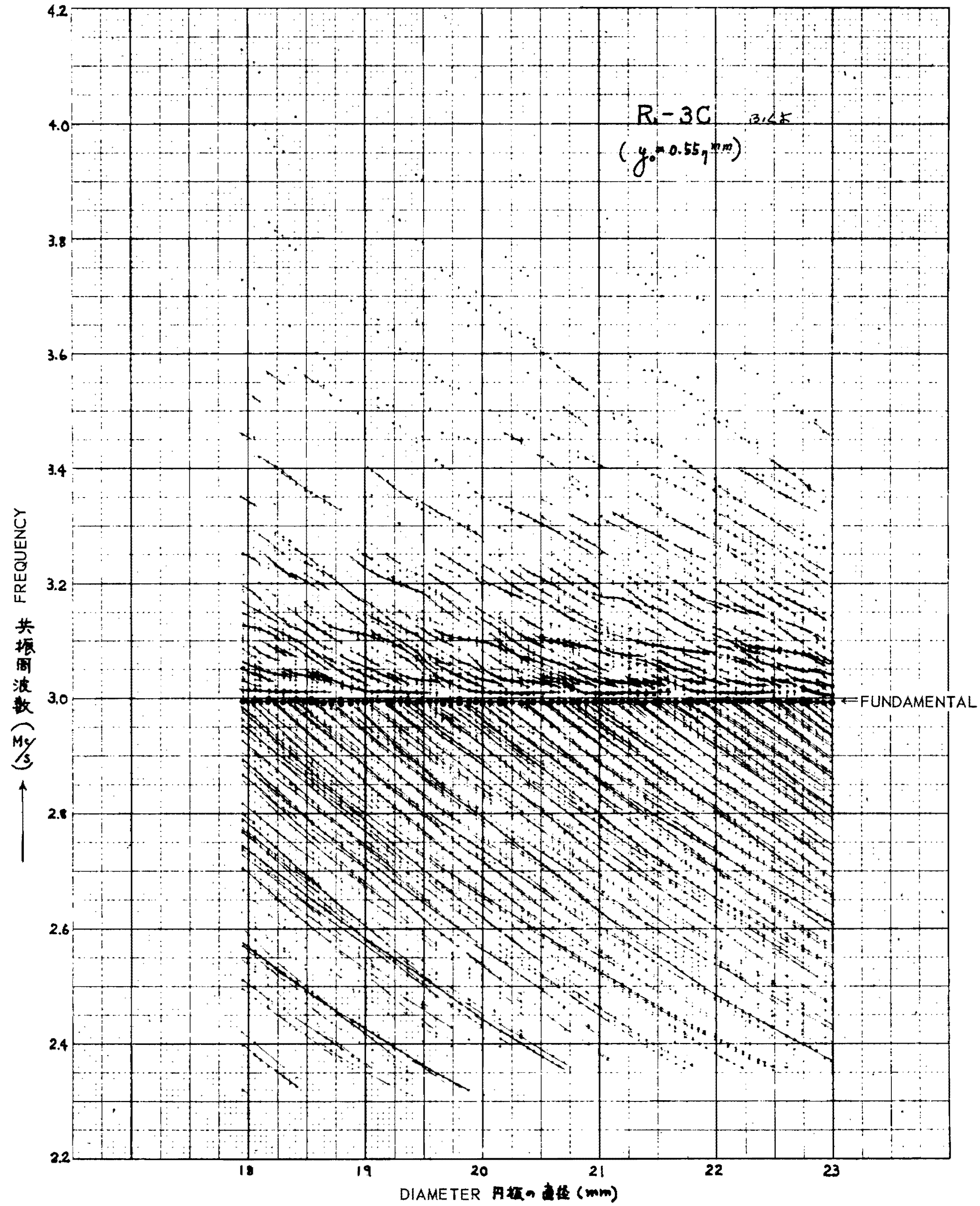


Figure 2. Mode Chart for a Circular Crystal Showing Relative Strength of All Responses by the Relative Sizes of the Dots.

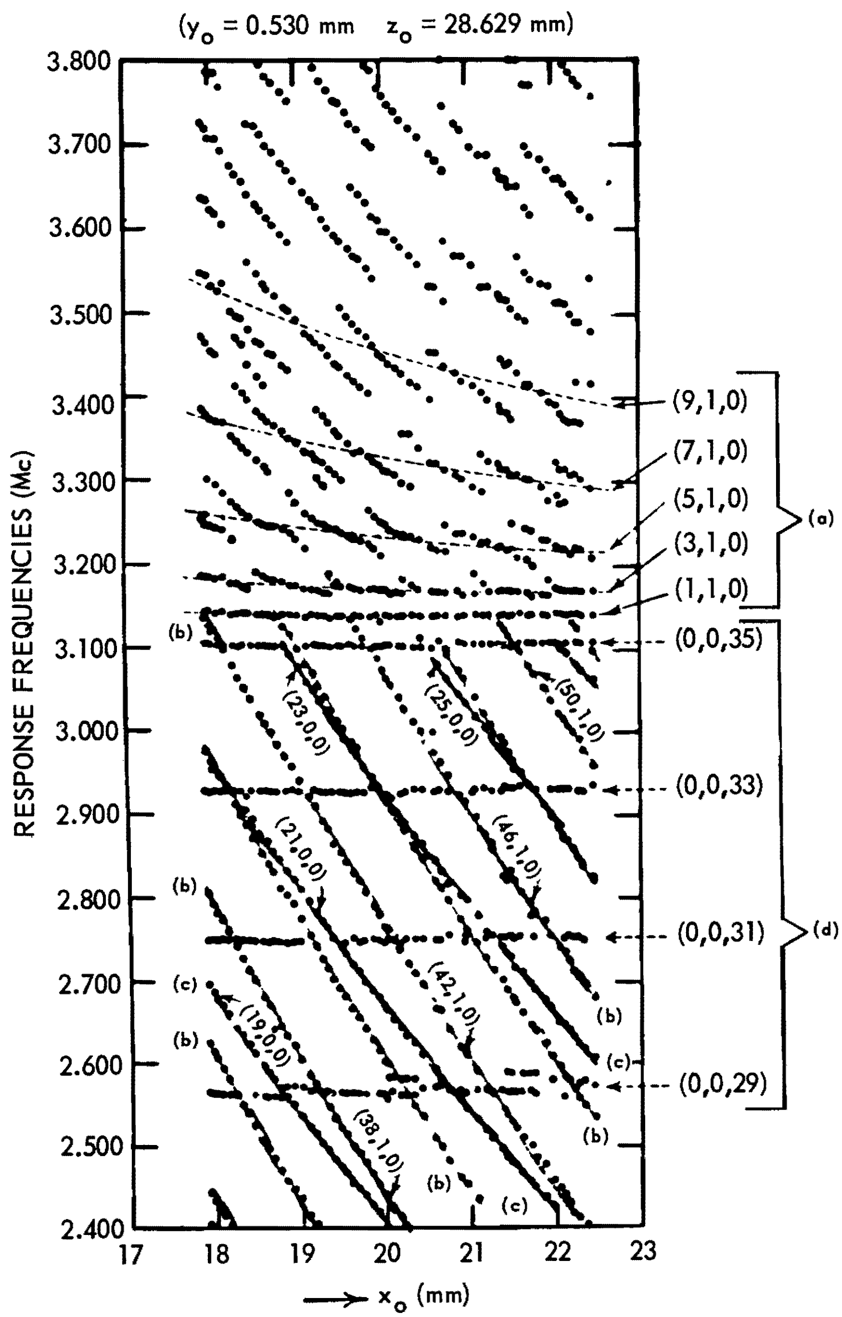


Figure 3. Mode Chart for a Rectangular Crystal Showing Stronger Responses. With the Rectangular Crystal There is a Clear Distinction Between "Strong" and "Weak" Responses.

is noted in the lower region of the mode charts; there, however, this series is only weakly coupled to other responses. In the lower region of the mode charts, additional responses are noted of which the frequency dependence on the abscissa dimension approaches inverse proportionality to this dimension.

Comparison of Figures 2 and 3 immediately indicates the greater complexity of the responses of the circular crystal. This complexity should be expected, however, because of the effects of the circular boundary.

The interpretation of the mode chart of the circular crystal has been guided by a detailed comparison of the mode chart of the circular crystal with that of the rectangular one.

b. Modes of Vibration. Particular crystal diameters were chosen at which some of the responses were expected to correspond to relatively simple crystal motions. These choices resulted from study of the mode chart in Figure 2 in the light of general knowledge of vibrating crystal plates and specific experience with rectangular AT-cut quartz plates. The diameters chosen were 22.19, 21.65, 20.39, 19.23, and 17. 93 mm (these diameters are indicated in Figures 4 and 14). The study of a particular response consisted of observing the polarization at various points on the surface of the crystal. The probe device described in Quarterly Report No. 1 of Contract No. DA-36-039 SC-78910 was used to produce a map of polarization for a crystal ground to a designated diameter when the crystal was excited at the appropriate frequency.

c. The Inharmonic Thickness-Shear Modes Above the Fundamental Shear Mode Frequency. Polarization surveys were made at the frequencies and diameters indicated in Figure 4. In one group of these surveys the polarization

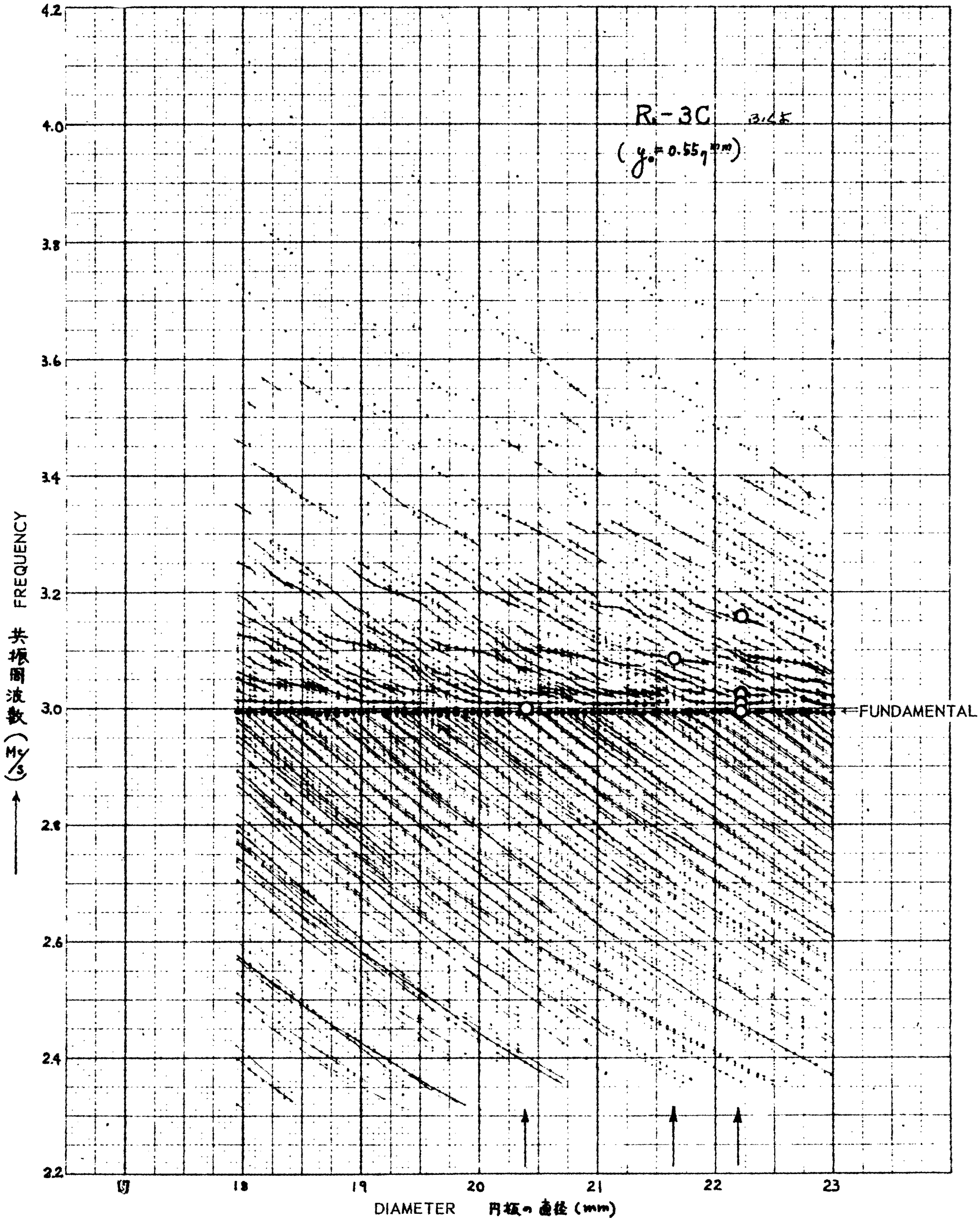


Figure 4. Diameters and Frequencies Above the Fundamental Thickness-Shear Frequency at Which Polarization Studies Were Made by the "Probe Method."

pattern exhibited no nodes for a traverse across the crystal in the z-direction, the polarization falling to zero only at the circumference of the plate. In the x-direction the polarization patterns of this group showed 1, 3, 5, and 7 major loops as the frequency was increased. These modes correspond to the modes of a rectangular crystal showing a single polarization loop along the z-direction and an odd number of loops in the x-direction. The corresponding modes of a rectangular crystal might be designated (1,1,0), (3,1,0), (5,1,0), and (7,1,0).[†]

Some examples of the polarization observed on these traverses are shown in Figure 5. The magnitude of polarization is here shown. Alternate maxima are of opposite sign (as a phase-sensitive detector has shown).

Figure 6 is a photograph of a contour model of polarization for the fundamental mode, a mode with one loop along the x-direction (1,1,0). This model was constructed by cutting out the polarization patterns recorded by the probe device as it traversed the crystal and mounting these cutouts on a wooden base.[††] Figure 7 is a similar contour model for a mode with five major loops in the x-direction (5,1,0).

Throughout this study, polarization patterns have corresponded closely enough to corresponding patterns observed on rectangular crystals to further justify the point of view of treating a circular crystal in terms of an "equivalent" rectangular one.

[†] The mode designation corresponding to that of the rectangular crystal is used for clarity of description. See Quarterly Report No. 1 of Contract No. DA-36-039 SC-78910.

[††] A similar contour model of the mode with three loops in the x-direction was included in the Final Report, Georgia Tech Projects A-402-1, -2, and -3, Quartz Crystal Studies and Measurements, 1 August 1958 to 28 February 1959. U. S. Army Signal Research and Development Laboratories Contract No. DA-36-039 SC-78910.

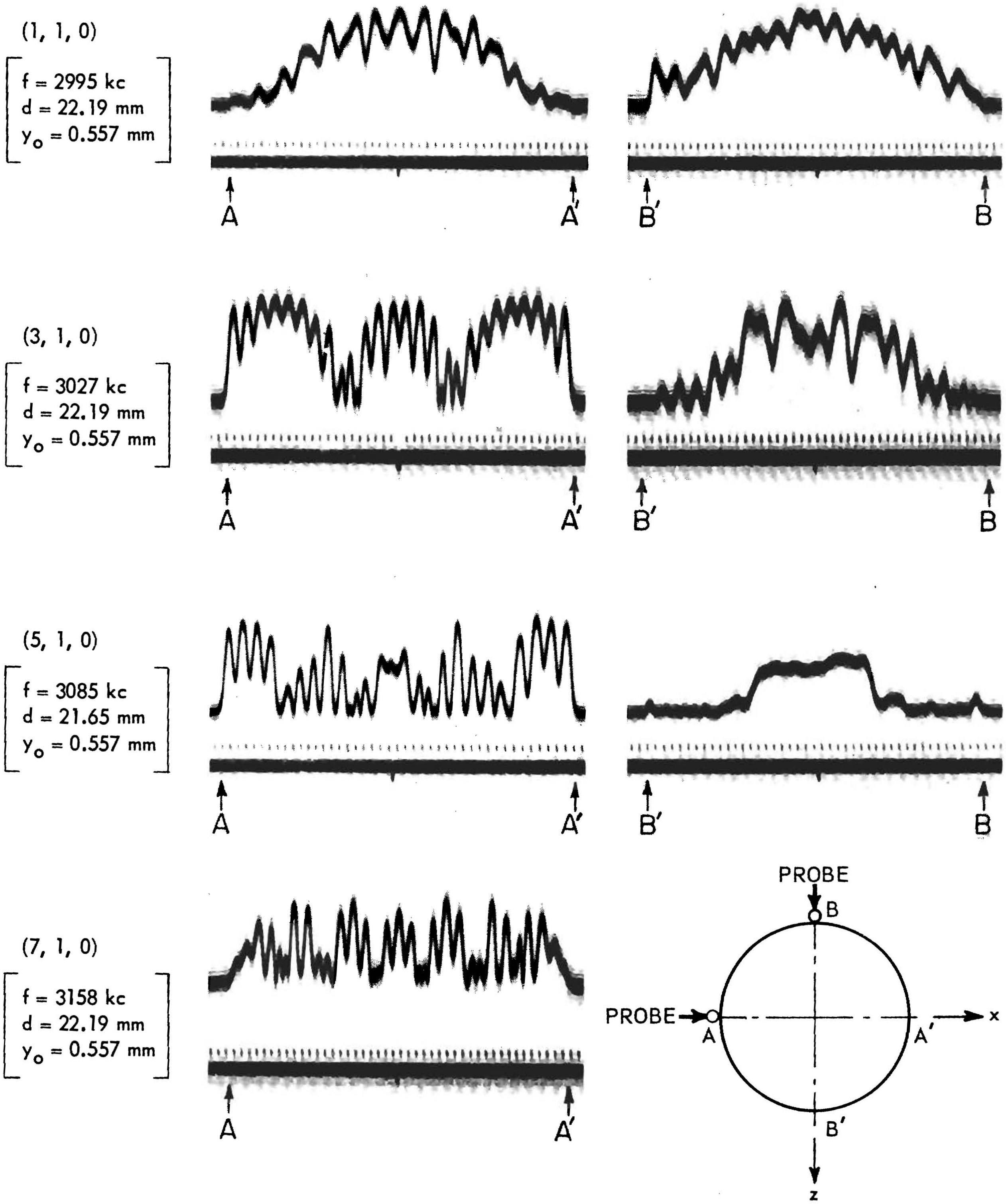


Figure 5. Examples of Polarization Patterns Observed Along x- and z-Diameters of a Circular Crystal Vibrating in Fundamental and Inharmonic Modes.

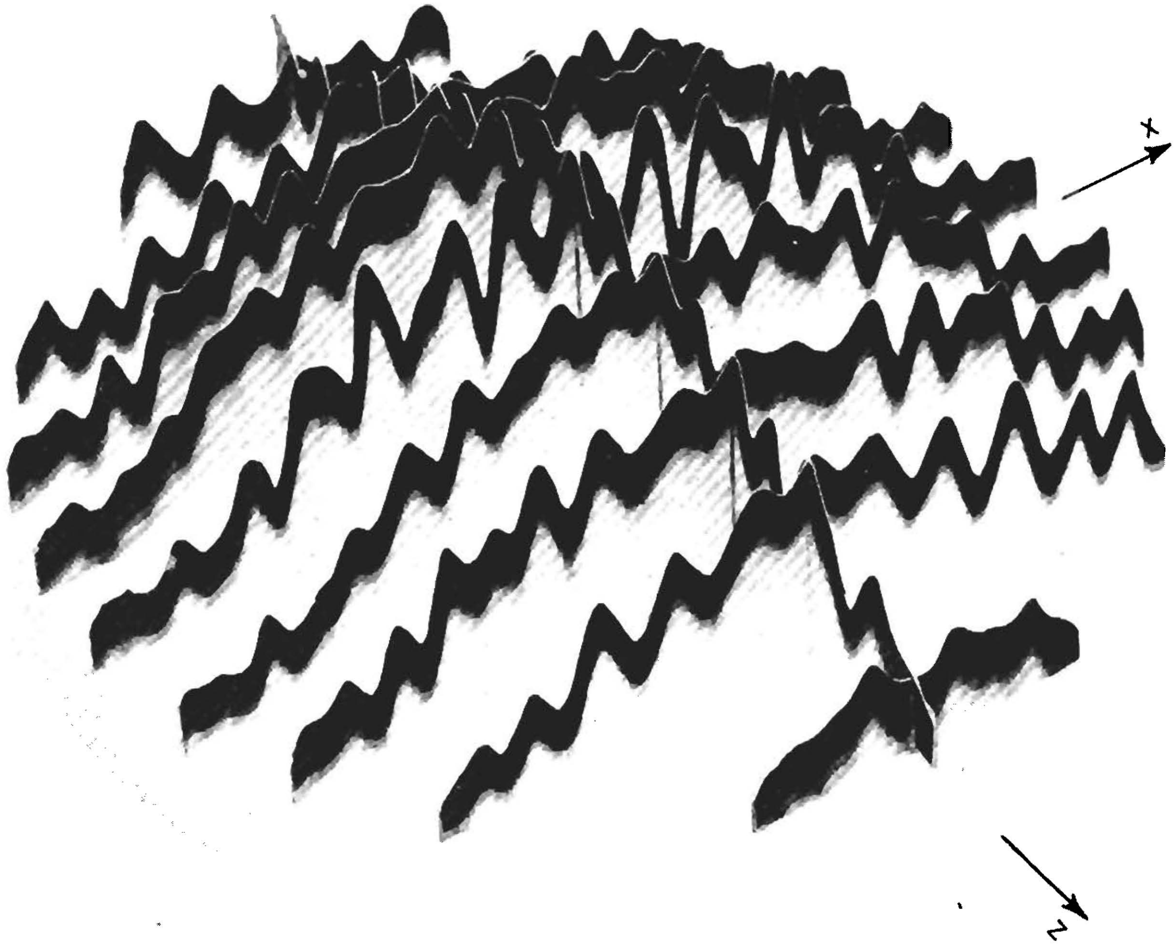


Figure 6. Contour Model of a Crystal Vibrating in the Fundamental Mode.

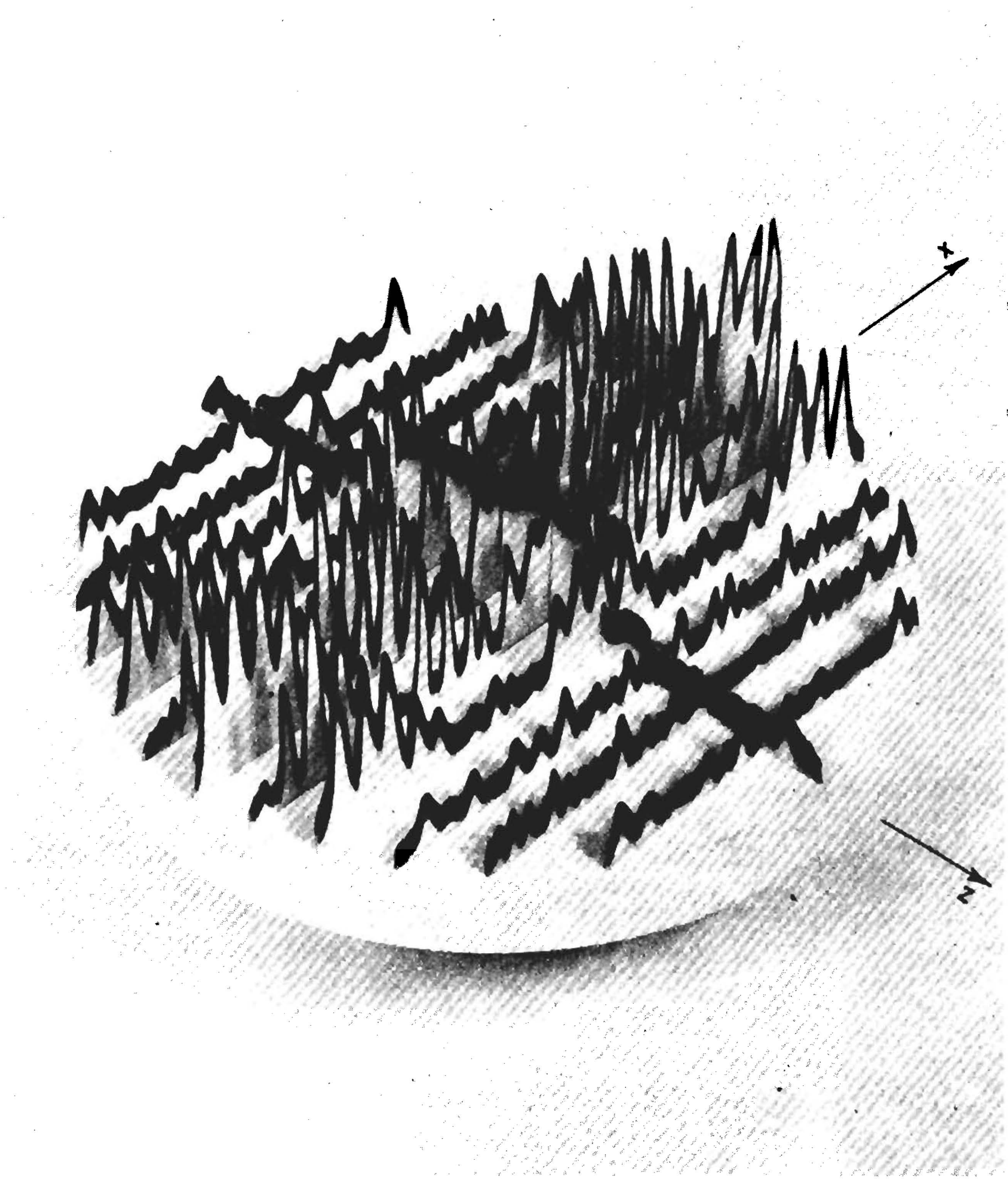


Figure 7. Contour Model of a Crystal Vibrating in the Fifth Inharmonic Overtone.

Another group of responses in the upper part of the mode chart, again neglecting coupling to the overtone contour modes (those sweeping up from the lower half of the mode chart), is characterized by a different polarization structure along the z-direction. One type of response in this group has a half-loop of polarization extending almost to the boundary of the crystal near each end of the z-diameter, two nodes, and a loop near the center of the crystal. A contour model of a response of this type having one loop along the x-direction (1,1,2) is shown in Figure 8. Along the z-diameter there is essentially one "wavelength" of polarization; the outer half-loops are centered almost over the edge of the crystal.

Another type of vibration in this region of the mode chart is one that is only weakly excited. Its symmetry would indicate that it could not be excited by a uniform electric field. The frequency of this vibration is very close to the fundamental thickness-shear frequency. The pattern obtained on some probe traverses when the crystal was vibrating in this mode is shown in Figure 9(a). When the sign of the polarization is taken into account, the polarization may be seen to be antisymmetric in the z-direction as sketched in Figure 9(b). Such an antisymmetric polarization pattern would not couple directly to the uniform electric field, hence the weakness of the response. However, the fact that the frequency of this mode is very close to the fundamental thickness-shear frequency makes this mode one of importance when a crystal is employed as a frequency control element. The corresponding mode in a rectangular crystal is (1,1,1).

Throughout the study a close similarity has been apparent between the polarization patterns of the circular and rectangular crystals vibrating in corresponding modes as well as the above-mentioned similarities of their

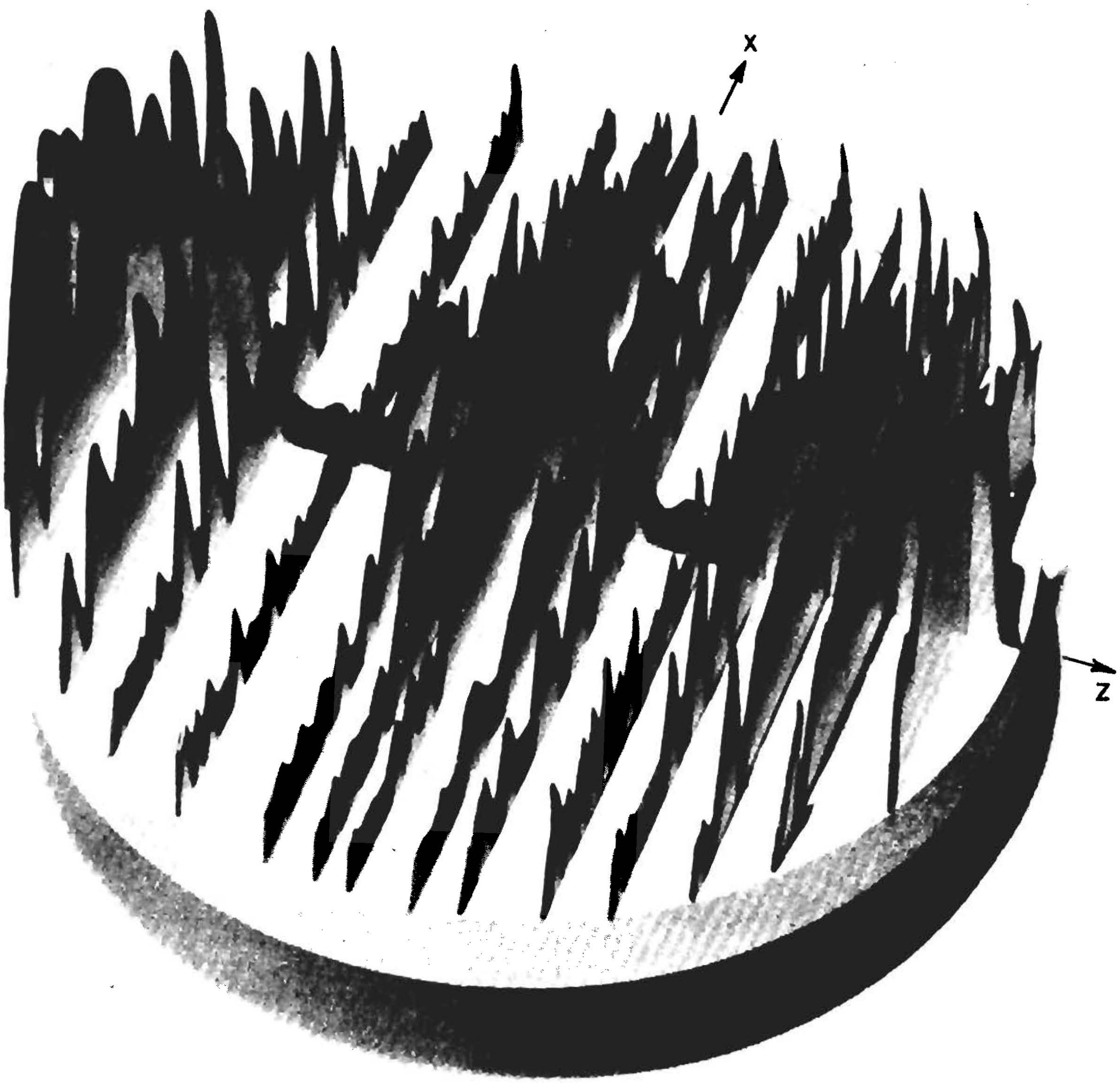


Figure 8. Contour Model of a Circular Crystal Vibrating in the Inharmonic Overtone Corresponding to (1,1,2) Mode of a Rectangular Crystal.

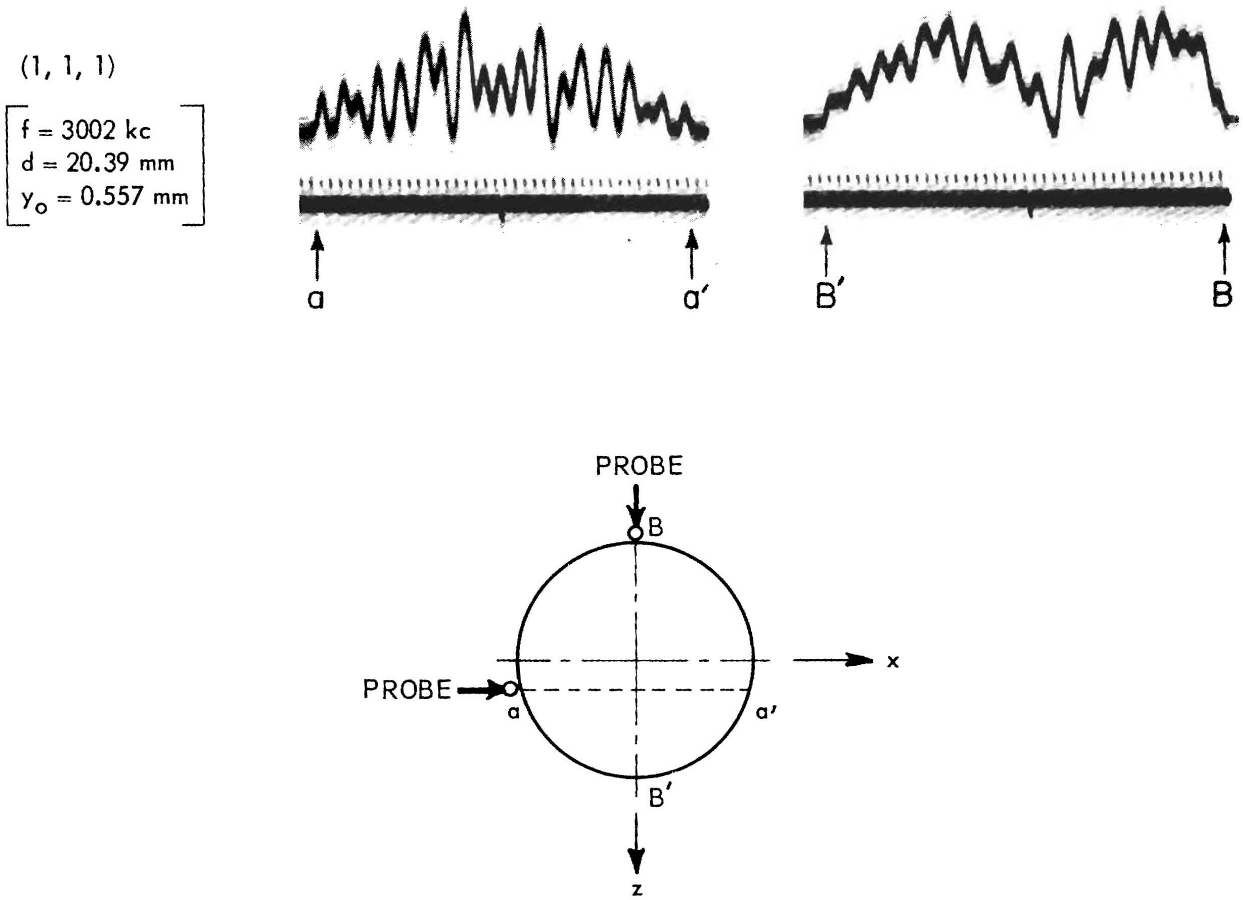


FIGURE 9. (a)

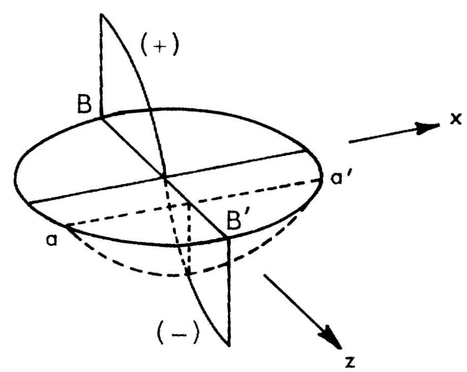


FIGURE 9. (b)

Figure 9. (a) Polarization Traverses of a Circular Crystal Vibrating in the Mode (1,1,1) of a Rectangular Crystal. (b) Distribution of Strain in this Mode.

mode charts. Consequently, the interpretation of the circular crystal in terms of an equivalent rectangular crystal appears attractive. The validity of this interpretation has been checked by comparison of the observed frequency-diameter relations computed for the equivalent rectangular crystal.

An equation for the response frequencies of a rectangular crystal in the fundamental and inharmonic thickness-shear modes is:[†]

$$f^2 = \frac{c_{11}}{4\rho}\left(\frac{p}{x_o}\right)^2 + \frac{c_{66}}{4\rho}\left(\frac{1}{y_o}\right)^2 + \frac{c_{55}}{4\rho}\left(\frac{r}{z_o}\right)^2 \text{, or, approximately,}$$

$$f = f_o\left[1 + 1.461 \cdot p^2 \cdot \left(\frac{y_o}{x_o}\right)^2 + 1.145 \cdot r^2 \cdot \left(\frac{y_o}{z_o}\right)^2\right] \qquad (1)$$

where f = the frequency of the response

f_o = the thickness-shear mode frequency of AT-cut plate in an infinite plane (almost the same as the fundamental frequency with a finite x_o and z_o for $x_o \gg y_o$, $z_o \gg y_o$)

$c_{11} = 85.45 \cdot 10^{10}$ dynes/cm^2

$c_{55} = 66.97 \cdot 10^{10}$ dynes/cm^2

$c_{66} = 29.25 \cdot 10^{10}$ dynes/cm^2

[c_{11}, c_{55}, and c_{66} are elastic constants of quartz crystal referred to the axes shown in Figure 1 of Quarterly Report No. 1 of Contract No. DA-36-039 SC-78910.]

ρ = the density of quartz crystal, 2.649 g/cm^3 at 20°C

p = number of half waves of polarization patterns along the x-direction, related to the order of the inharmonic overtone

r = number of half waves of the polarization pattern along the z-direction, and related to the order of the inharmonic overtone

x_o, y_o, z_o = the dimensions of the rectangular crystal plate.

[†] I. Koga and H. Fukuyo, "Vibration of Thin Piezoelectric Quartz Crystal Plates, Especially an R_1 cut (AT-cut) Rectangular Plate," Journal of the Institute of Electrical Communication Engineers of Japan, 36, No. 345, 59-67, February 1953 (in Japanese).

Equivalent lengths of the sides of the rectangular crystal may be defined:

$$\left.\begin{aligned} x_o &= \psi_1 d \\ z_o &= \psi_2 d \end{aligned}\right\} \tag{2}$$

where d = diameter

ψ_1 = the ratio of the equivalent x-dimension to the diameter

ψ_2 = the ratio of the equivalent z-dimension to the diameter

With this substitution, Equation (1) becomes:

$$f = f_o \left[1 + 1.461 \cdot p^2 \cdot \left(\frac{y_o}{\psi_1 d} \right)^2 + 1.145 \cdot r^2 \cdot \left(\frac{y_o}{\psi_2 d} \right)^2 \right] \tag{3}$$

The values of ψ can be determined from response measurements of a specific crystal. For the crystal diameter, x_o = 22.2 mm, and thickness, y_o = 0.557 mm, the observed frequency of the fundamental thickness-shear mode, f_o, is 2995.0 kc/sec. For the third inharmonic thickness-shear mode (3,1,0) the observed frequency, f, is 3023.0 kc/sec. These values substituted in Equation (3) give a relation between ψ_1 and ψ_2. For the (1,1,2)-type of inharmonic overtone, the observed frequency is 3005.2 kc/sec. The corresponding values substituted in Equation (3) provide a second relation between ψ_1 and ψ_2. The solution of the simultaneous equations gives the values:

$$\psi_1 = 0.893$$

$$\psi_2 = 0.920$$

In actual practice it is convenient to work with the difference equation:

$$\Delta f = f_o \left[1.461 \cdot (p^2 - 1^2) \cdot \left(\frac{y_o}{\psi_1 d} \right)^2 + 1.145 \cdot r^2 \cdot \left(\frac{y_o}{\psi_2 d} \right)^2 \right]. \qquad (4)$$

Now, instead of depending on the measurement of the absolute values of the frequency, the Δf between the fundamental and the appropriate inharmonic overtone may be used for deriving the values of ψ.

In Figure 10 the frequency difference computed from Equation (4) as the diameter is varied is shown by a line superposed on the mode chart for each mode examined. The computed frequency differences of inharmonic overtones from the fundamental thickness-shear vibration may be seen to coincide with the experimental data to a good approximation, and this agreement indicates that the equivalence concept is a reasonable one. Extension of the direct analysis of the circular crystal to the detail achieved for the rectangular crystal has not yet been attempted.

Figure 11 is a sketch of the equivalent rectangular crystal superposed on the circular crystal for these groups of responses above the fundamental thickness-shear mode frequency.

d. Modes Prominent at Frequencies Below the Fundamental Thickness-Shear-Mode Frequency. In the region of the mode chart below the fundamental thickness-shear-mode frequency two groups of modes are found. For members of one group, the frequency increases as the diameter is reduced in a manner suggestive of the flexural† modes of the rectangular crystal (type b). However, several times as many modes of this type occur in the mode chart for

†In earlier reports on this and the preceding contract, the term shear-flexural mode was used. It is now believed that this mode is a simple flexural mode which should be designated (p,o,o).

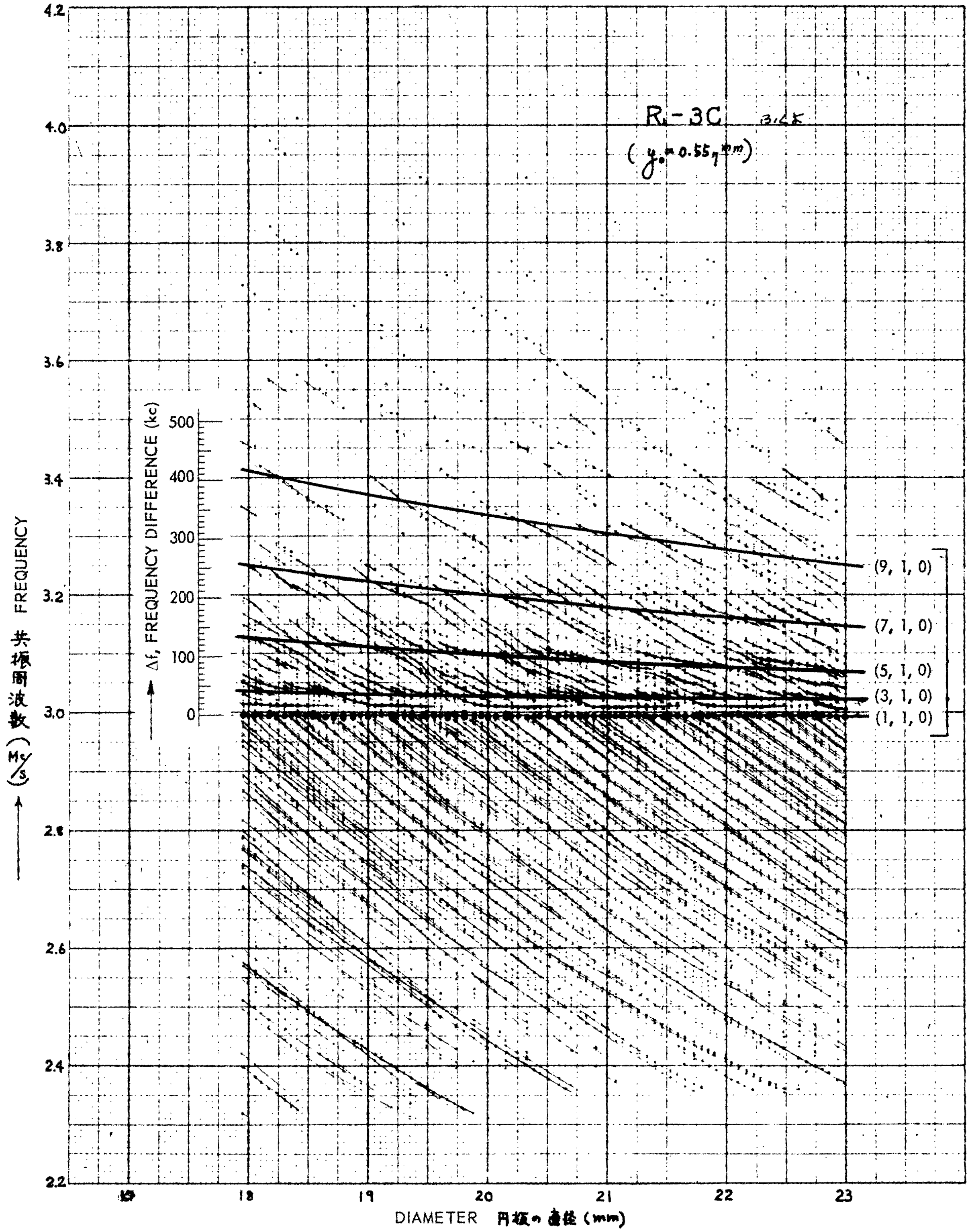


Figure 10. Frequencies of Inharmonic Modes Computed from Equation 4 Superposed on the Mode Chart of Figure 2.

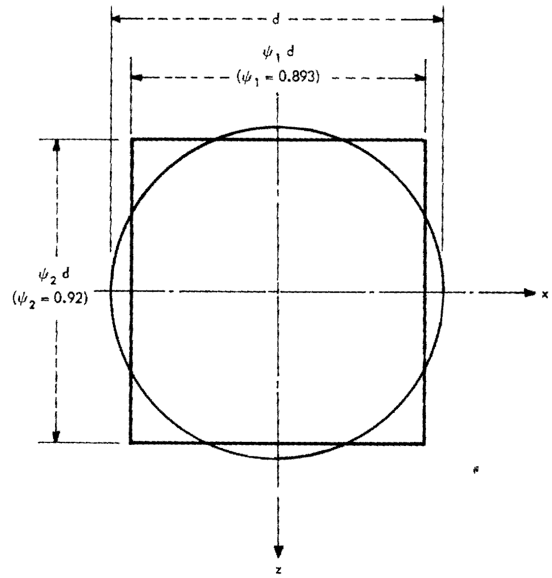


Figure 11. Schematic of a Circular Crystal and Its Equivalent Rectangular Crystal for the Inharmonic Modes.

the circular crystal as are found for the flexural modes of a rectangular crystal.

Many polarization patterns were taken for circular crystals vibrating in modes of this group. Out of studies of these polarization patterns a subgroup emerged that seems to be simple flexural modes. The polarization pattern along the x-diameter for these modes is very similar to that of a rectangular plate along the x-direction. Strong polarization extends only about 1/8 diameter each side of the x-diameter. Figure 12 shows a polarization traverse along the x-diameter of a crystal vibrating in the 44th shear-flexural mode (44,1,0) In this case, as well as with the above-mentioned thickness-shear vibrations, the concept of an equivalent rectangular crystal is used. Figure 13 is a sketch of the equivalent rectangular crystal superposed on the circular crystal for this subgroup of responses. The equivalent length of the rectangular crystal,

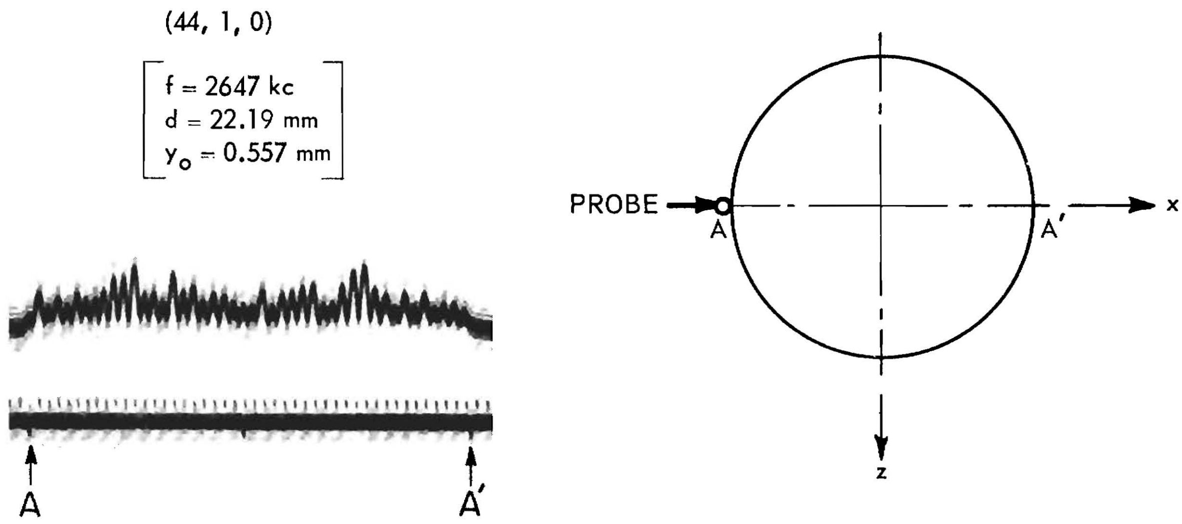


Figure 12. Polarization Traverses Along the x-Diameter of a Circular Crystal Vibrating in the 44th Flexural Mode.

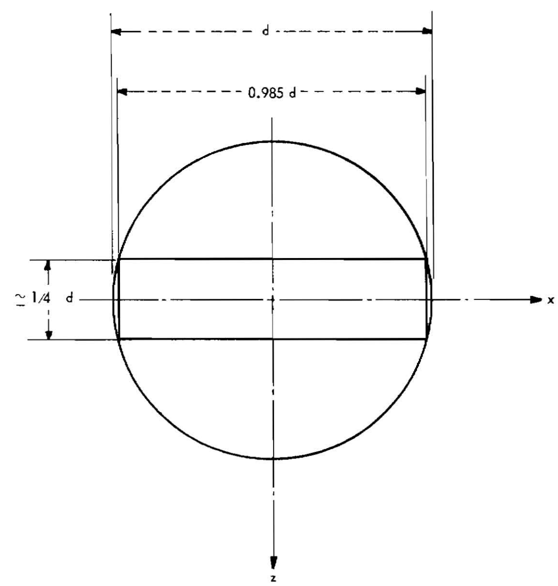


Figure 13. Schematic of a Circular Crystal and its Equivalent Rectangular Crystal for the Shear-Flexural Modes.

0.985 diameter, was derived from comparison of the mode charts, Figures 2 and 3.

The use of this concept of an equivalent rectangular crystal and experimental data about the frequency-versus-x_o relations of the rectangular plate made possible the selection of other modes of this type from the maze of responses in this frequency region; flexural overtones from the 36th to the 48th were identified. Figure 14 is the mode chart of Figure 2 with the flexural modes of the equivalent rectangular plate superposed. These curves for the equivalent rectangular crystal were taken from the observations previously made on rectangular AT-cut quartz crystals (see Figure 3).

In between and approximately parallel to the trends of the flexural modes sketched in Figure 14 lie the responses of several other modes.

The form of the polarization patterns of the lesser responses of successive modes as the frequency is increased above that of one of the flexural modes (indicated in Figure 14) is outlined in the sketches of Figure 15. The lower sketch shows the distribution of the polarization of the principal flexure mode confined to the region along the x-diameter. At the higher frequency of the next minor mode the pattern is broadened in the z-direction, but shortened in the x-direction. At each succeeding minor response this trend is progressively greater. In the area of strong polarization near the center of the crystal, the standing waves in the x-direction are clear enough so that the overtone order can be estimated from the wavelength. The overtone order in each case is the same as that of the principal flexural mode of lower frequency.

These modes cannot be identified at present in any strict sense. The form of the frequency-versus-diameter locus, parallel to the flexural trend, and the order of overtone suggest that these are also flexural vibrations, possibly with some complications similar to those of inharmonic overtones.

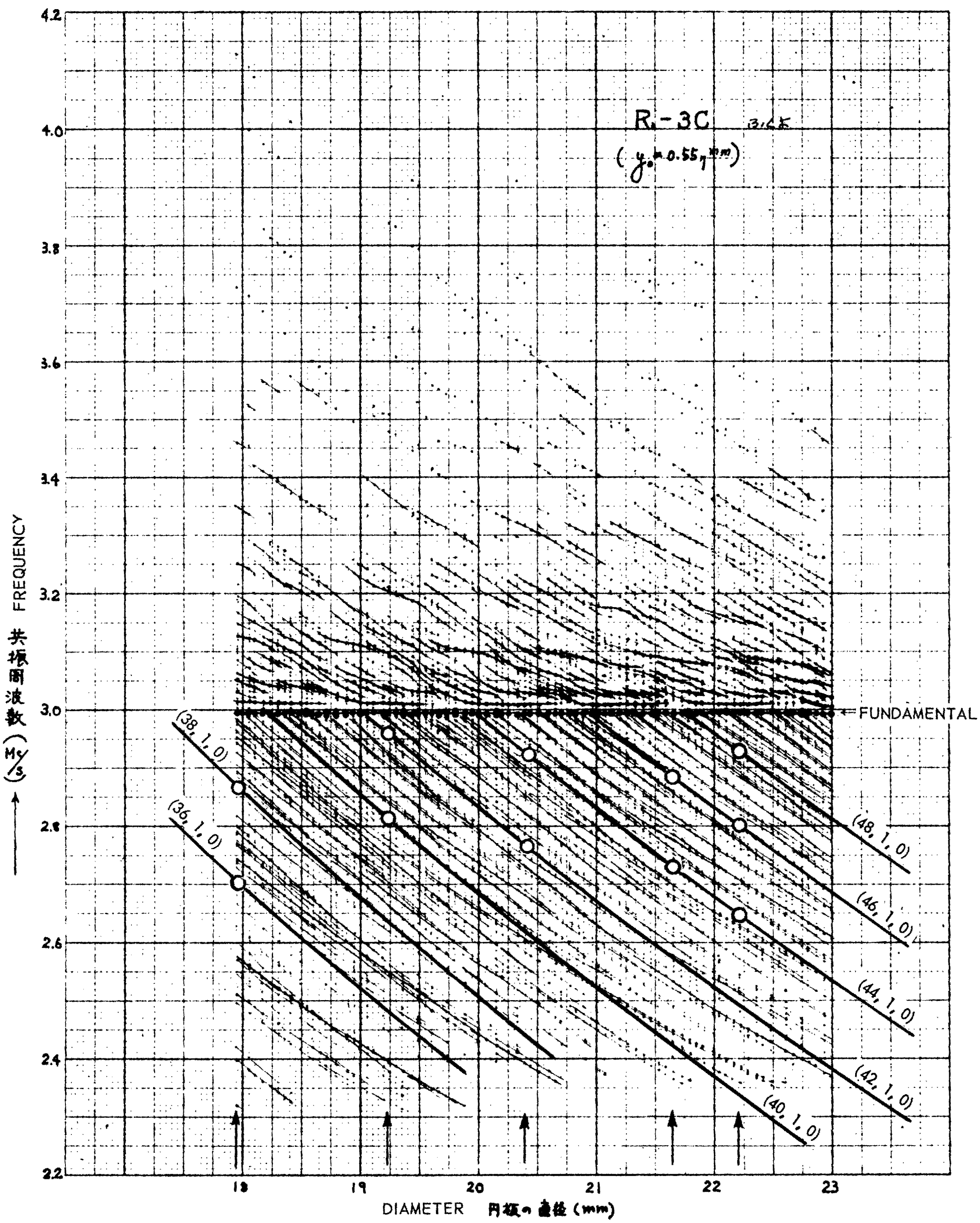


Figure 14. Frequency-Diameter Relations for Flexural Modes of the Equivalent Rectangular Crystal.

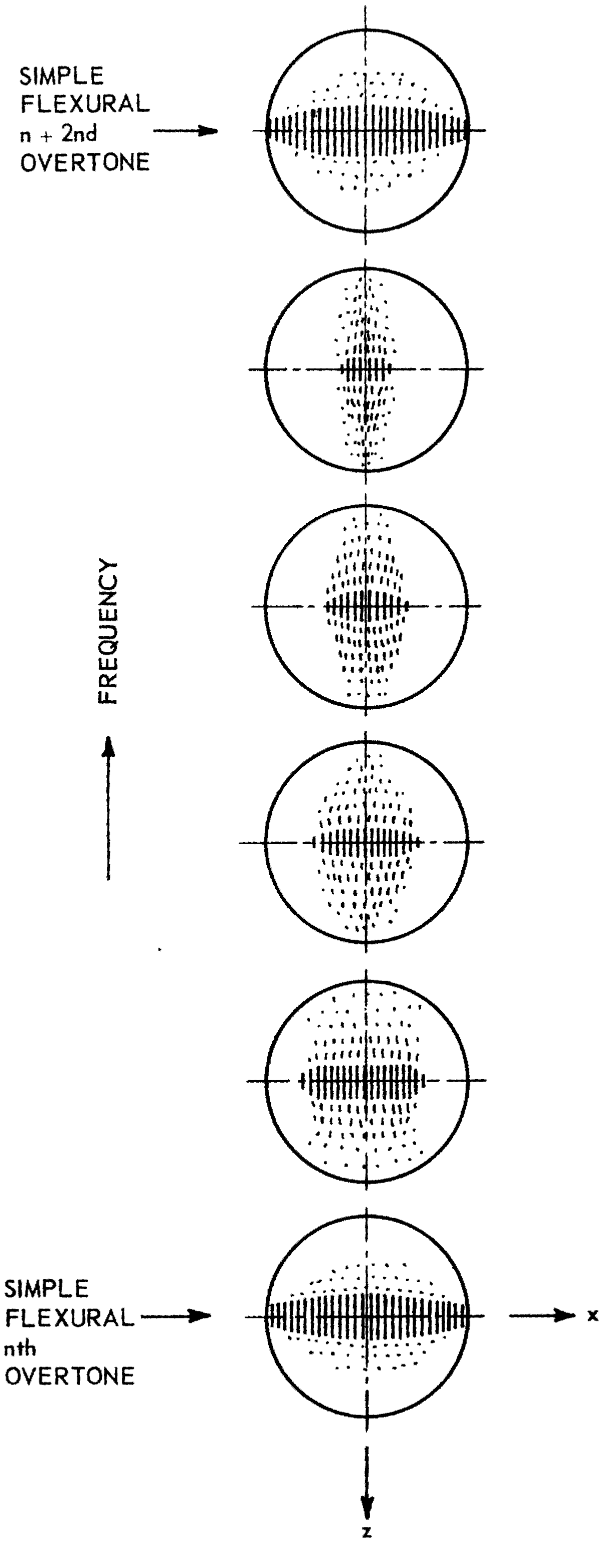


Figure 15. Schematic of the Polarization for Two Adjacent Simple Flexural Vibrations and the Nonsimple Flexural Vibrations Occurring at Intermediate Frequencies.

Since these modes are not observed separately in the rectangular crystal they appear to be a result of the circular boundary of these crystals. A possibility exists that in a rectangular crystal these modes have frequencies coincident with the flexural modes or that they are not excited at all. This question could be decided by starting with a rectangular crystal and successively grinding off the corners until it became circular. Somewhere in the process these modes should become evident. If they were degenerate with the flexural modes in the rectangular case then on a mode chart they would be seen to split off from the flexural modes as the originally rectangular crystal approached the circular form. On the other hand if they were absent in the rectangular case then they would be expected to come into existence, first weakly, and then more strongly, at frequencies separate from the frequency of the flexural modes as the incremental grinding changed the originally rectangular crystal into a circular one.

A second group of responses with the frequency trend somewhat less steep than the first group has been examined. In this case the polarization patterns indicate standing waves inclined about 45° to the x- or z-axes. From the frequency and the overtone order of one vibration of this type estimates were made of the frequencies of others of the same type. With these estimates as a guide other modes of this type were found. Figure 16 shows the trend of these vibrations and overtone orders.

The analysis has not exhausted all measured responses. Other families of modes may well exist.

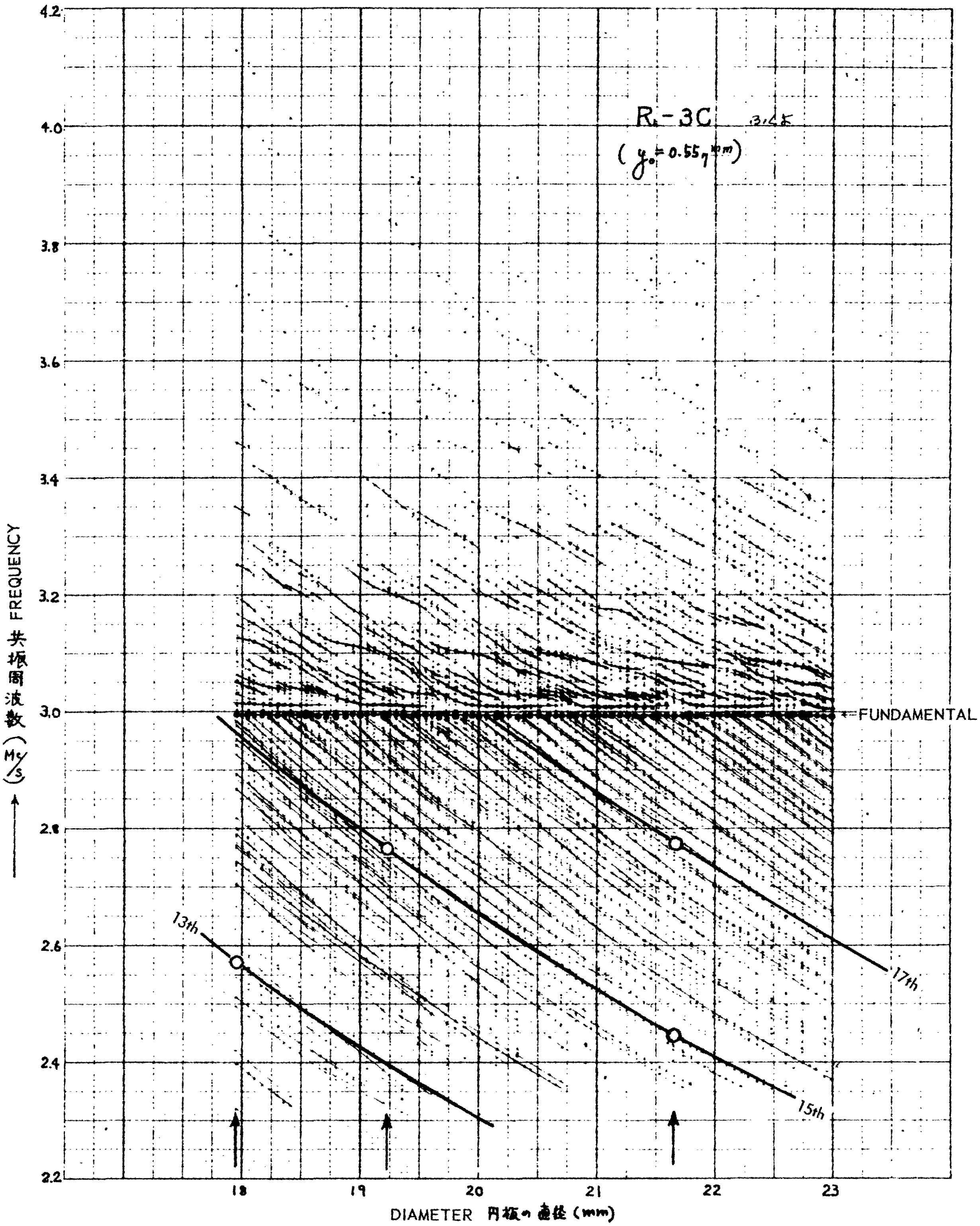


Figure 16. One Class of Overtone Vibrations and the Diameters and Frequencies at Which Polarization Studies Were Made.

3. Feasibility Studies with Beveled Circular Crystal Plates

Five beveled circular AT-cut crystal plates were obtained for study of polarization patterns and spectra. Four of the plates were chipped at the edges to different extents. For the initial studies, the plate without chips (A) and the plate with the largest chip (B) were chosen. Dimensions of the two plates are shown in Figure 17. The orientation of the x- and z-axis were determined by means of polarized light.

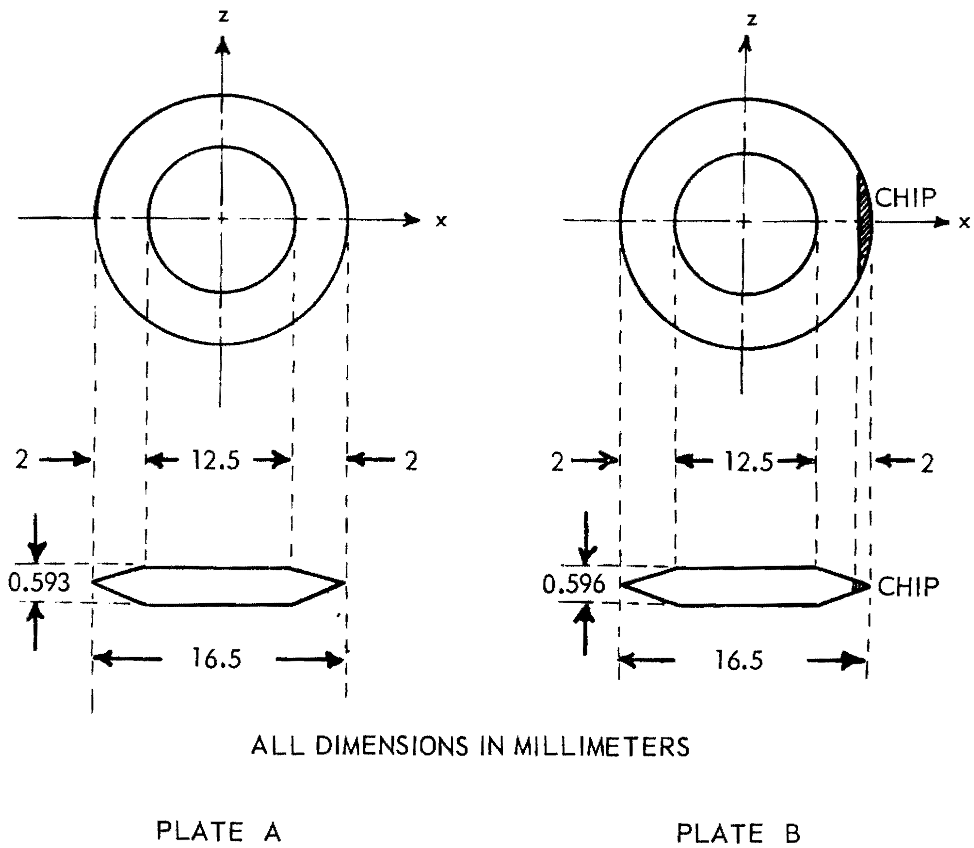
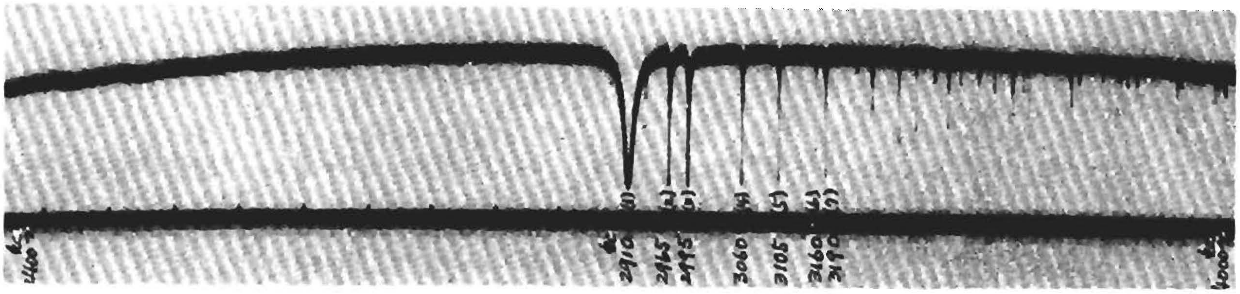
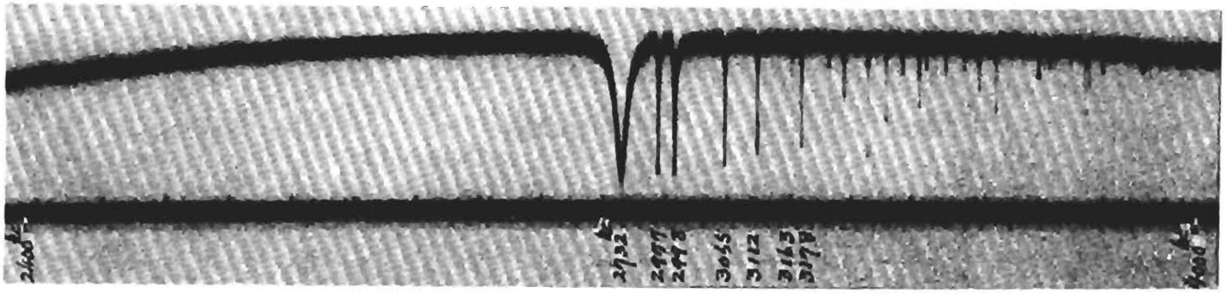


Figure 17. Beveled Circular Test Crystal Plate.

Figure 18 shows the amplitude-versus-frequency spectra for the two plates. The frequencies of several of the stronger responses are marked on the



A. BEVELED PLATE A



B. BEVELED PLATE B

Figure 18. Amplitude-Versus-Frequency Spectra of Two Beveled Circular Plates.

oscillograms. These beveled circular plates show no significant responses below the frequency of the principal thickness-shear vibration and no strong responses close to this frequency on the upper side.

For the polarization studies, the crystal plates were placed between two plane electrodes of diameter larger than the plates. Thus, the effects of polarization at the beveled surfaces could not be observed clearly. Figure 19 shows the polarization patterns for plate A along the x- and z-axis diameters for each of the seven major responses shown in Figure 18.

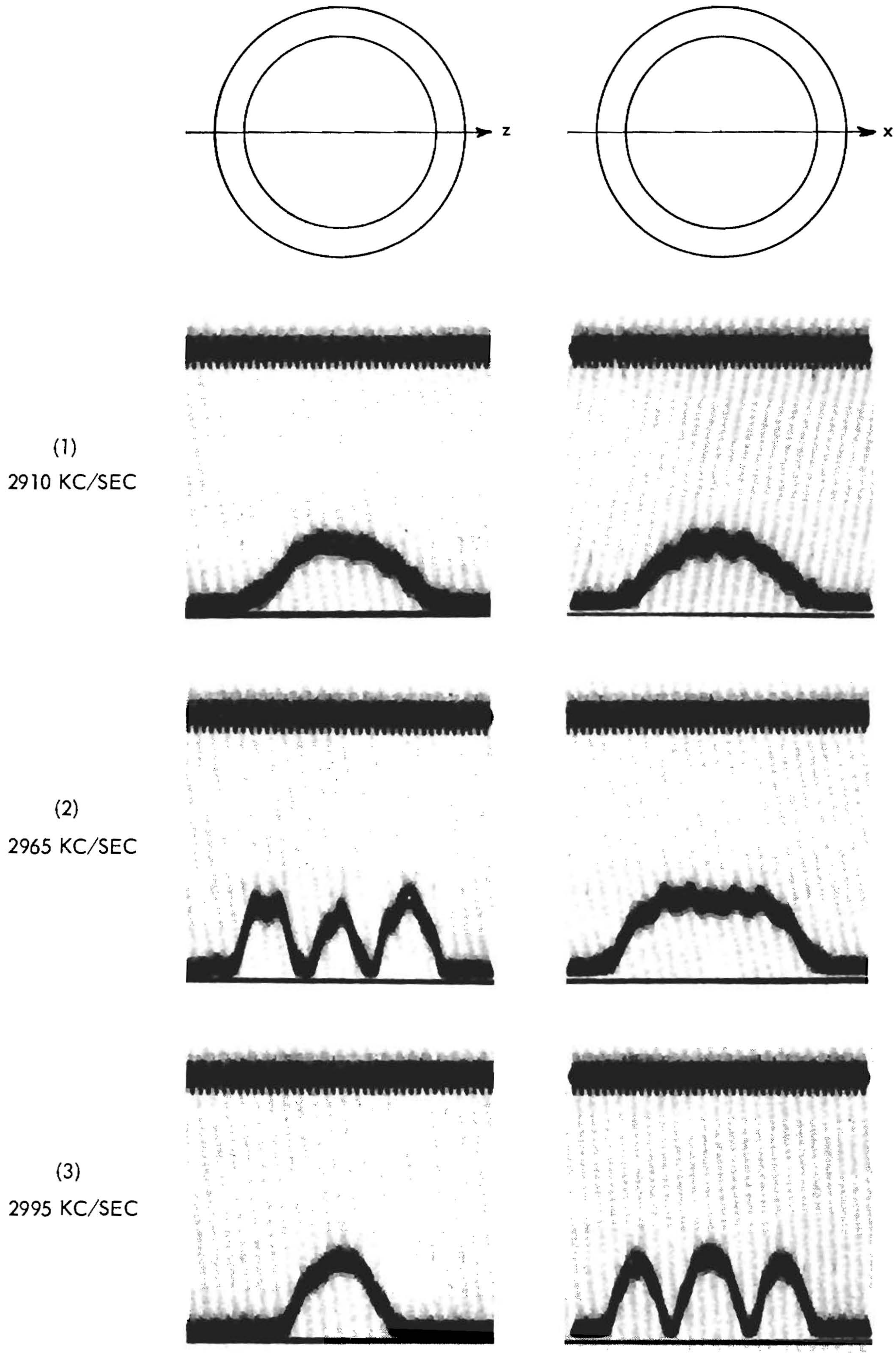


Figure 19. Polarization Patterns of Crystal Plate A.

(4)
3060 KC/SEC

(5)
3105 KC/SEC

(6)
3160 KC/SEC

(7)
3190 KC/SEC

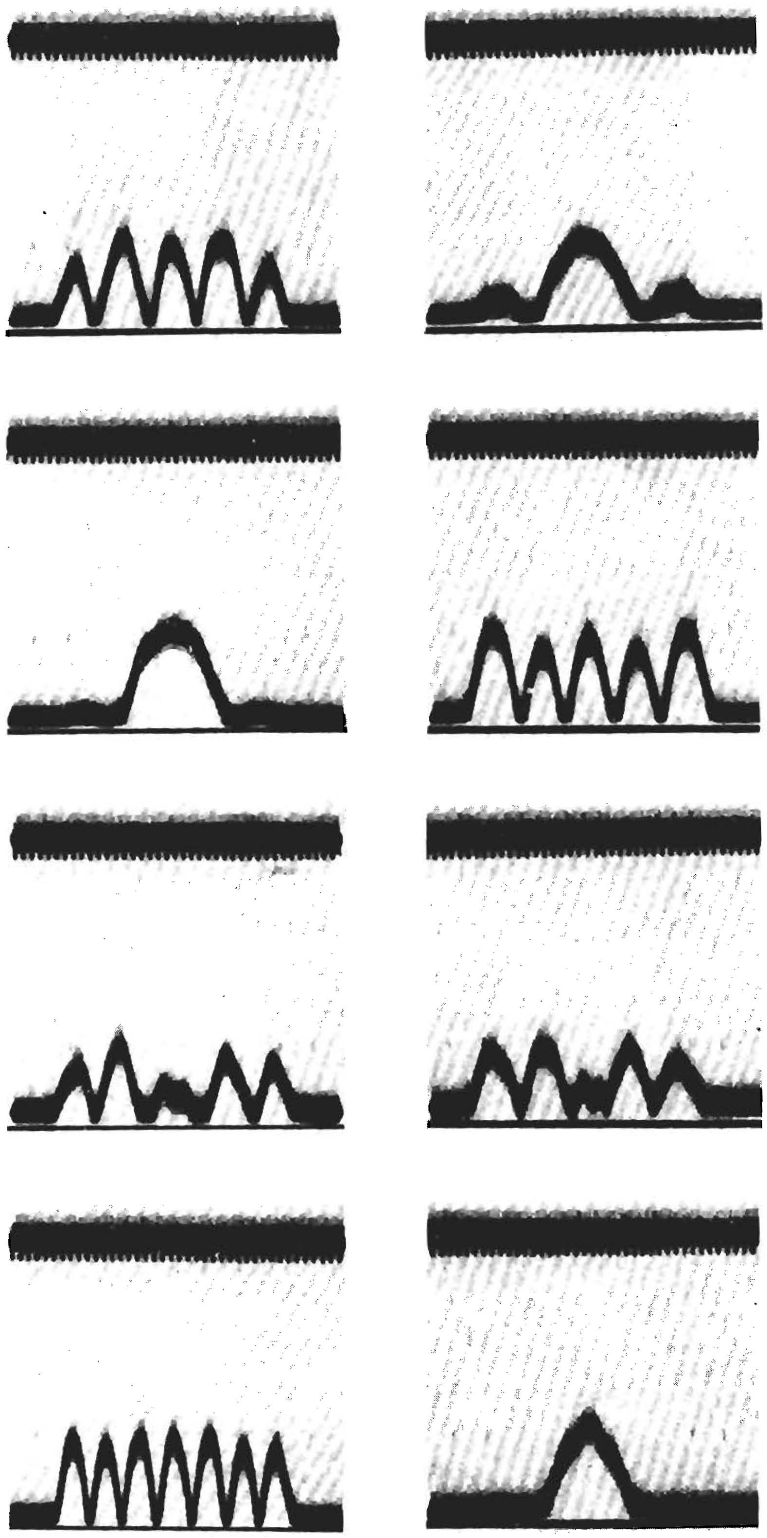


Figure 19 (Continued). Polarization Patterns of Crystal Plate A.

The preliminary measurements indicate that available techniques can be used to clarify the behavior of the beveled circular crystal; however, this work will be deferred until the rectangular crystals are more fully understood.

4. Feasibility Studies with Triangular Crystal Plates

Brief investigations of the polarization and spectra of a typical 3-mc/sec triangular crystal plate were performed. The amplitude-frequency spectrum is shown in Figure 20. The polarization patterns corresponding to

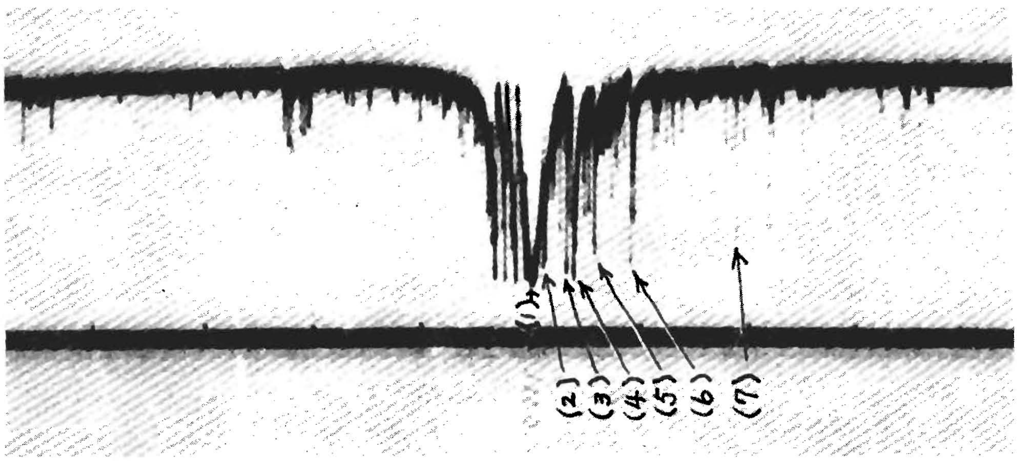
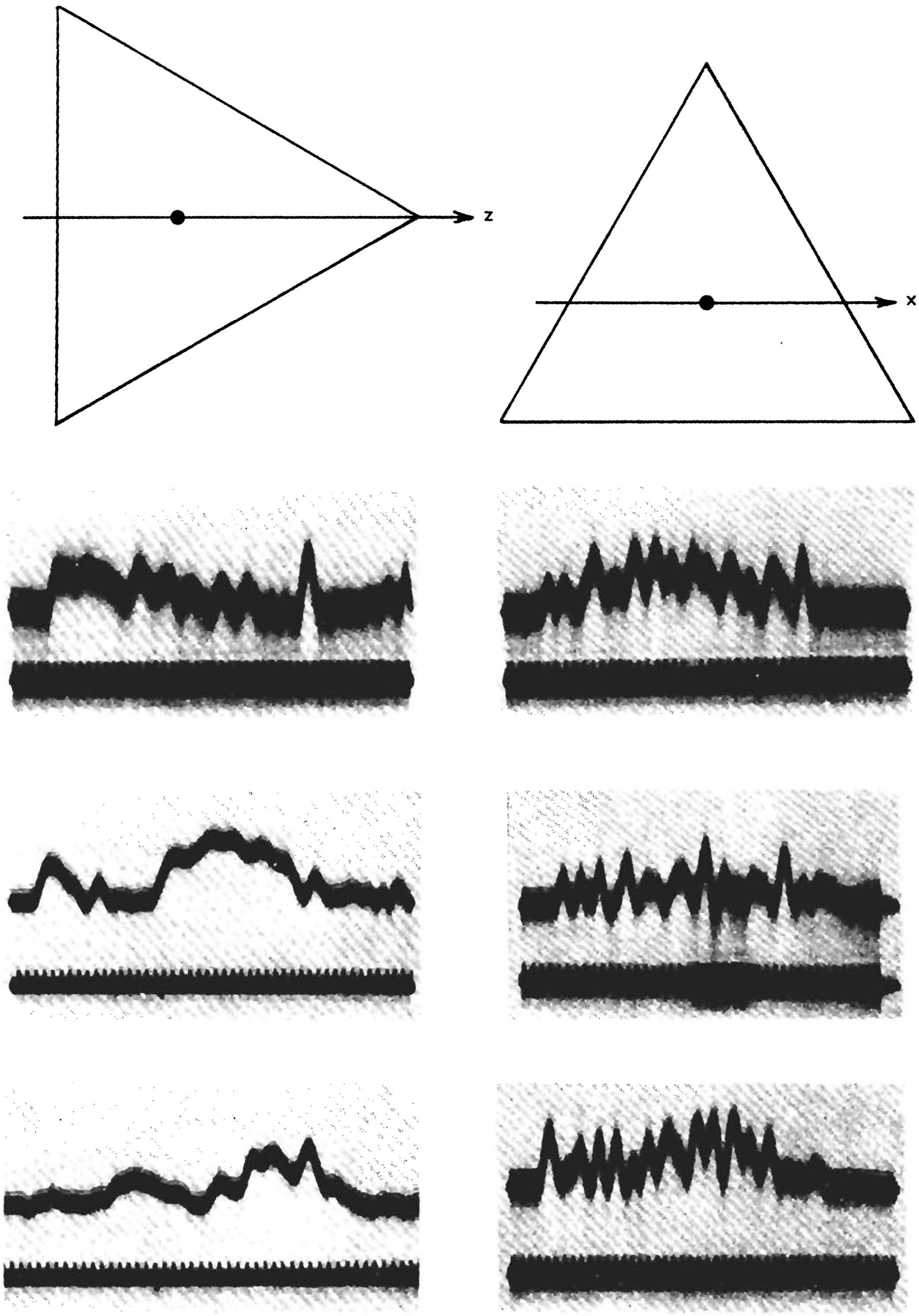


Figure 20. Amplitude-Versus-Frequency Spectrum of a Triangular Crystal Plate.

stronger responses of Figure 20 are shown in Figure 21. The polarization patterns were obtained along both the x-axis and z-axis, through the center of the plate as indicated in Figure 21.

The original five triangular crystal plates supplied by the USASRDL could not be examined since they were ground to a frequency of 10 mc/sec and the measurement equipment is designed to operate at 3 mc/sec. Accordingly, five crystal plates with the following specifications were procured:



(1)
2987 KC/SEC

(2)
2996 KC/SEC

(3)
3014 KC/SEC

Figure 21. Polarization Patterns of the Triangular Crystal.

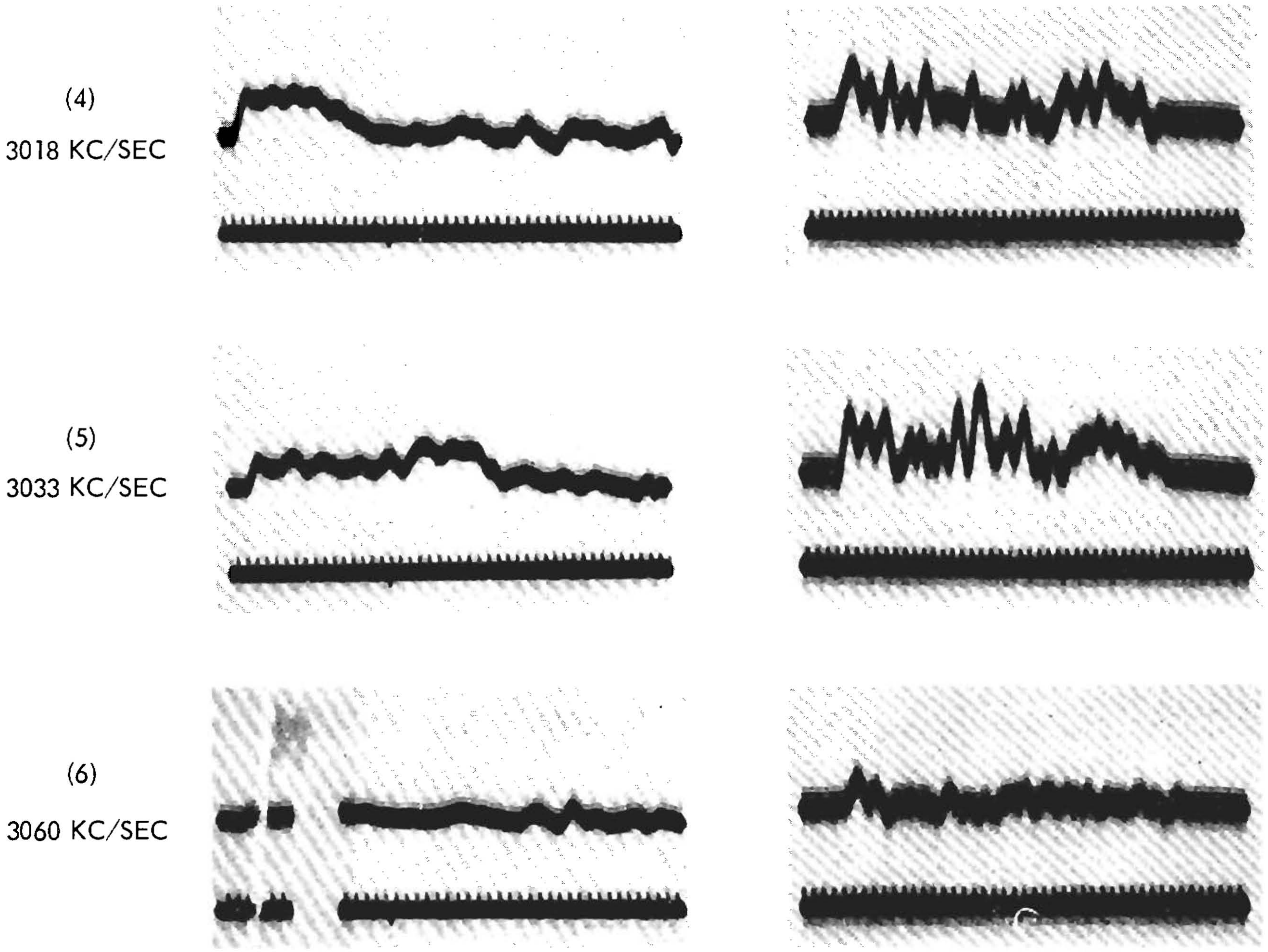


Figure 21 (Continued). Polarization Patterns of the Triangular Crystal.

Cut:	AT at an angle of 35° 15' ± 2'. Orientation of the five plates to be within 2 minutes of each other.
Frequency:	3 mc/sec ± 10 kc/sec for the fundamental thickness-shear mode.
Shape:	Triangular, equilateral.
Dimensions:	1.000 inch ± 0.010 inch each side; one side along the x-axis, ± 1°.
Operational Temperature:	25 ± 5°C.
Thickness:	As required by frequency.
Surface:	Milky white polish or, if necessary to obtain the required thickness, optical polish.

Four of the five crystals were chipped at one or more places on the edges when received. The plate without chips was chosen for the investigations.

The complexity of the vibrational patterns for the triangular plate is greater than that of the rectangular plate. The optimum design parameters for a specific crystal type can be determined only by changing the dimensions of the crystal and analyzing the various spectral responses and polarization patterns. For crystals in the shape of an equilateral triangle, the spectrum will be a function of the side-length and the specific orientation, where the specific orientation, ψ, is defined in Figure 22. Whether or not optimum selections of these quantities exist can be determined only by extensive studies.

5. Measurement of Rectangular Crystal Plates in the Vicinity of the Third Overtone

a. Equipment for Spectrum and Polarization Studies. During August 1959 the equipment which was used by Dr. Fukuyo was returned to Japan. Mr. Tsuzuki brought similar equipment to this country from the Yokahama National

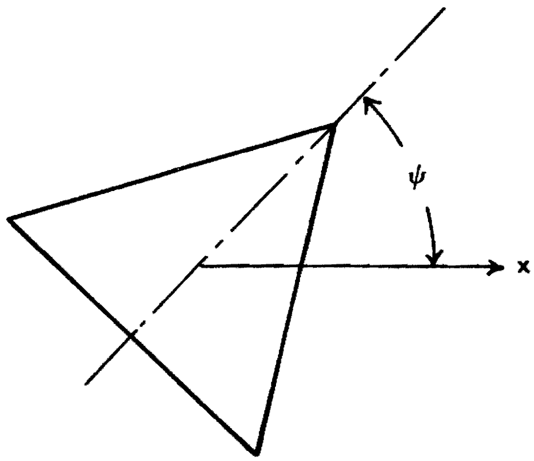


Figure 22. Definition of Specific Orientation, ψ.

University. Figure 23 is a block diagram of the equipment for recording the spectra.

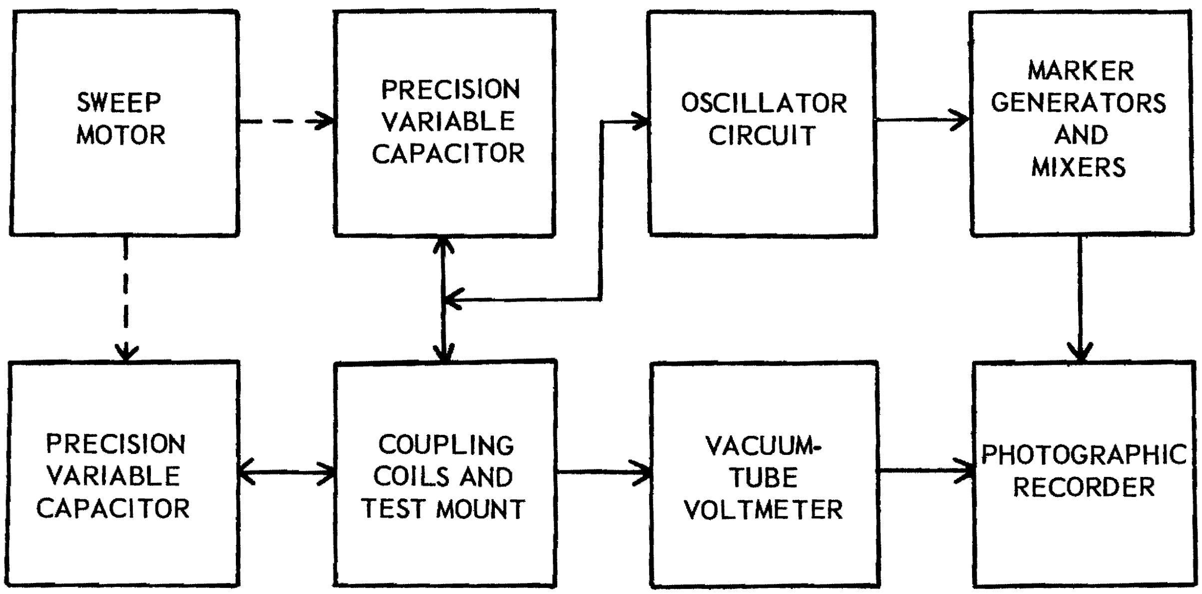


Figure 23. Block Diagram of the Equipment for Recording Spectra.

A schematic representation of the precision capacitors, coupling coils, and crystal test mount is shown in Figure 24. The capacitors, manufactured by

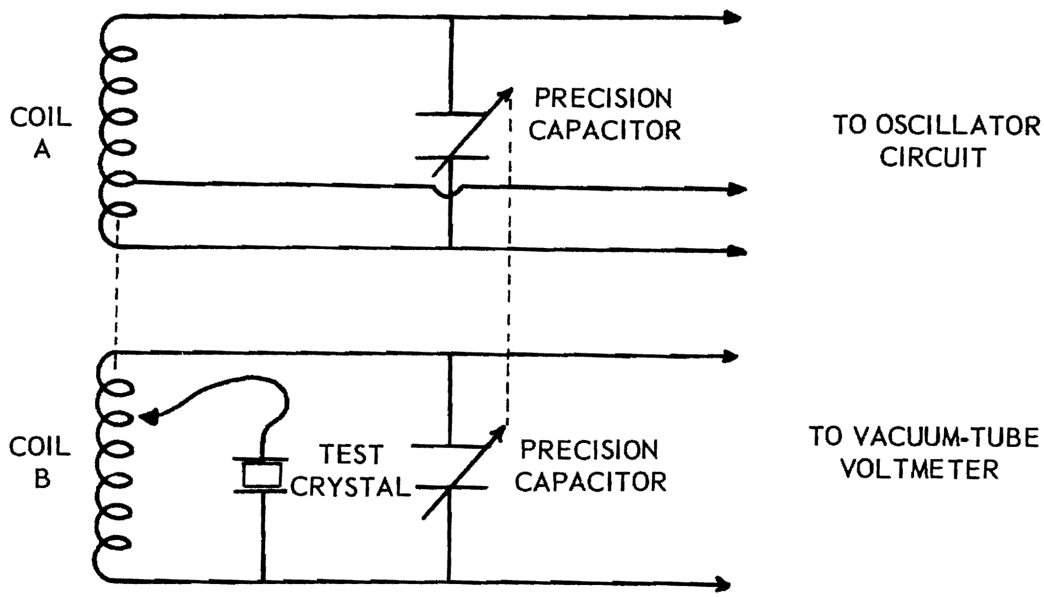


Figure 24. Elements of the System for Measurement of Spectra.

the Yokogawa Electric Works in Japan, have an approximately linear frequency variation with mechanical rotation. The coils A and B are constructed as nearly identical as possible so that proper tracking of the two resonant circuits can be obtained with the capacitors coupled mechanically. The magnetic coupling between the coils is made as small as the sensitivity of the vacuum-tube voltmeter permits. A tap on coil A is provided for oscillator feedback. Taps on coil B provide for adjustment of the excitation level of the test crystal. The full (100%) coil tap was used for the measurements near the third overtone.

Lack of perfect tracking of the two tuned circuits and lack of constant oscillator output cause the baseline of the recordings to vary somewhat with frequency. These variations are of little concern, however, since only the frequency and relative magnitudes of the responses are of importance in the present study.

The complete oscillator-detector circuit assembly is shown in Figure 25. Japanese vacuum tubes are presently used; however, American tubes with the same or corresponding numbers may be substituted.

The improved resolution of this equipment over previous recordings is made possible by the improved oscillator stability, the improved mechanical drive arrangement, and the direct injection of frequency markers. Two dispersions have been used regularly; ± 35 kc/sec for the expanded spectrum and ± 400 kc/sec for the wide-range spectrum, both centered on the frequency of 3 mc/sec.

The photographic recorder is also manufactured by the Yokogawa Electric Works. Three vibrators are provided for three separate recording channels. The center vibrator, known as a type H vibrator, is used for the spectrum recordings and has a sensitivity of 10 mm/ma and a frequency response of 500 cps. The other vibrators are type A with a sensitivity of 0.5 mm/ma and a frequency response of 2 kc/sec.

The frequency markers are provided by three crystal-controlled oscillators and a system of mixers. The oscillators operate at 10, 100, and 3000 kc/sec to provide strong frequency components with 10-kc/sec spacing in the region of 3000 kc/sec. These frequency components are mixed with the output of the crystal drive oscillator and the low-frequency heterodyne component is recorded by one of the type A vibrators. The other type A vibrator is not used.

The photographic recorder and the test crystal drive-oscillator are driven by separate synchronous motors. Thus, the frequency variation on the recorded chart is approximately linear and interpolation may be used between the 10-kc/sec markers.

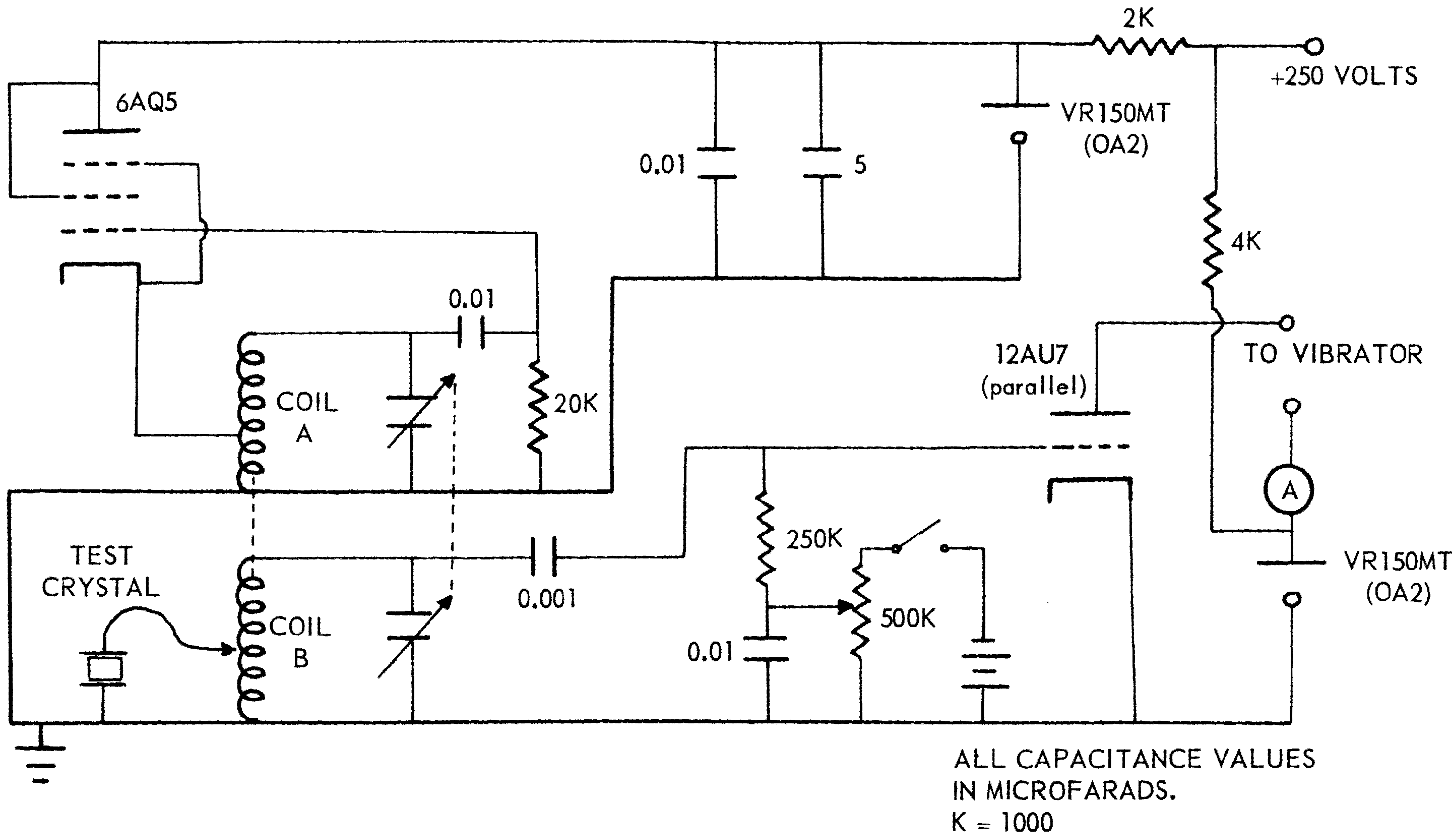


Figure 25. The Oscillator-Detector Circuit Diagram.

The spectrum measurement equipment was calibrated by the substitution of known resistors for the test crystal, Figure 26. The ordinate, recorder galvanometer relative displacement, is unity for an infinite resistor (or crystal resistance). In practice, the impedance is so low for the principal response that the minimum was used for the zero-point, although cut-off of the oscillator is preferable. The unity deflection varies somewhat with the frequency but is readily available between responses. The approximate motional resistance of a crystal response can be evaluated from this calibration.

Equipment for making polarization studies was placed in operation in September 1959. This equipment consists of the necessary mechanical drive equipment, the source generator, and the detector-recorder equipment outlined in Figure 27. The equipment is similar to that used by Dr. Fukuyo.

The probe mount consists of a metal platform much larger than the crystal plates. A small probe is mounted flush with the platform. A sliding mechanism is arranged to transport the crystal over the probe. Electrical contact with an upper electrode is made by a flexible wire. The metal platform is used as the lower crystal electrode as shown in Figure 28. In Dr. Fukuyo's equipment the same photographic oscillograph was used for recording both the polarization patterns and the spectra. With this instrument immediate observation of the polarization patterns could not be made. In the current equipment a Varian Model G-10 pen recorder has been substituted.

Because of the much lower frequency response of the Varian recorder (one second for full-scale travel), the linear sweep speed across the crystal had to be reduced to approximately 10 mm/min. The lower speed required improved frequency stability of the signal generator. Further improvements in stability were necessitated by the contemplated measurement of weak responses. The General Radio Type 1001-A Signal Generator, presently in use, has only

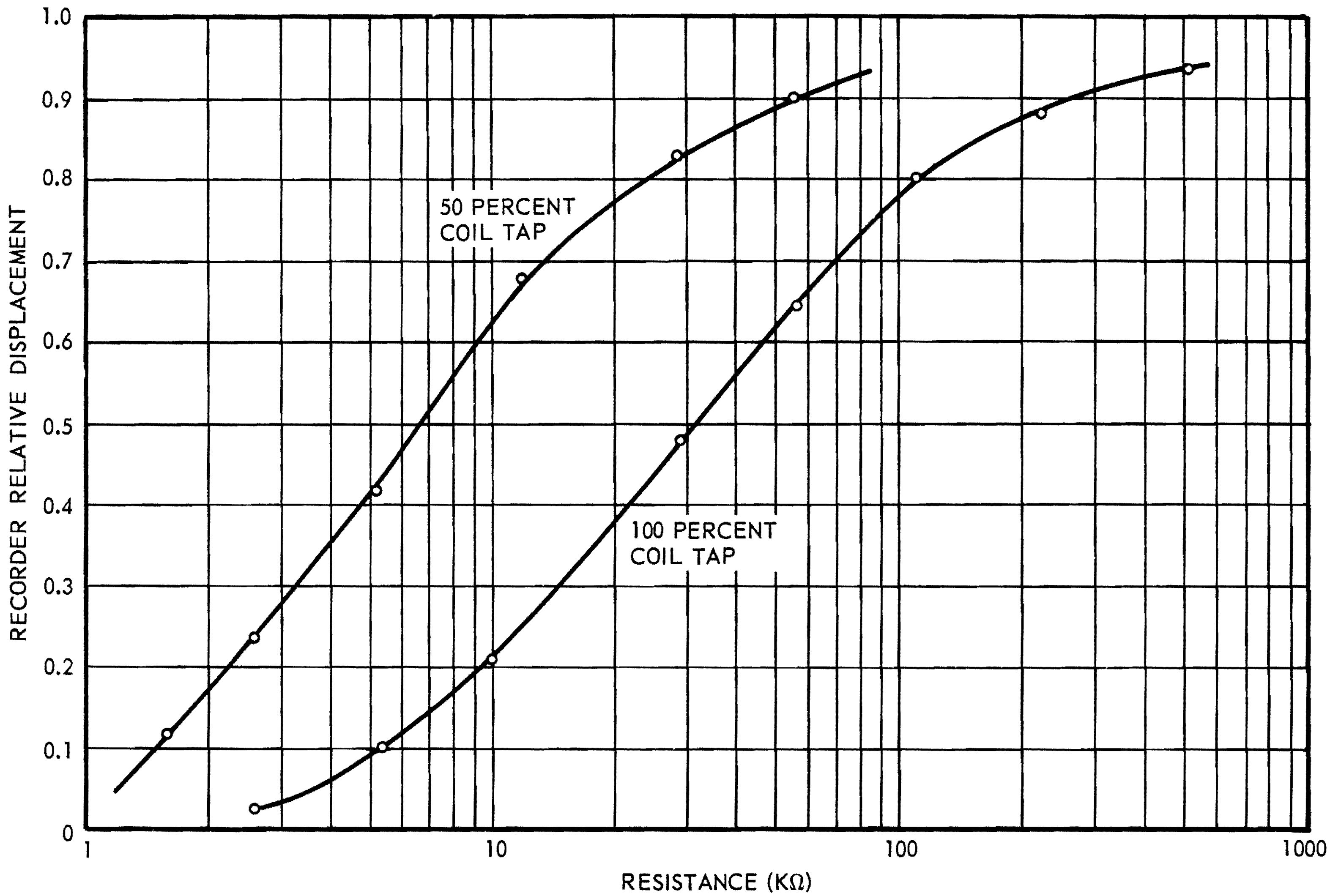


Figure 26. Motional Resistance Calibration of the Spectrum-Measuring Equipment.

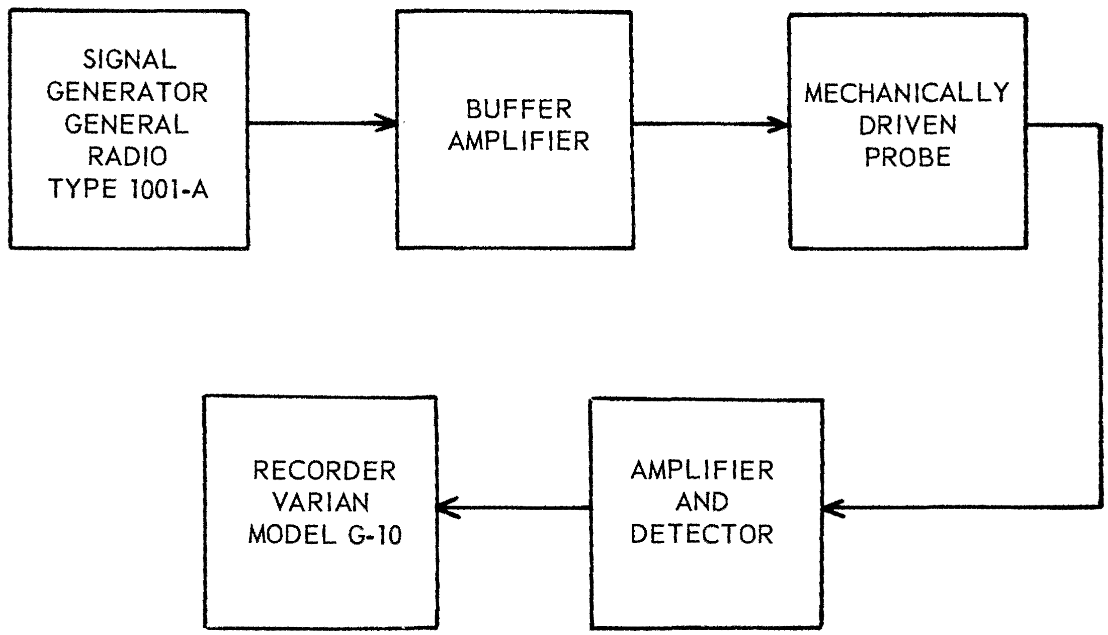


Figure 27. Block Diagram of Equipment for Polarization Studies.

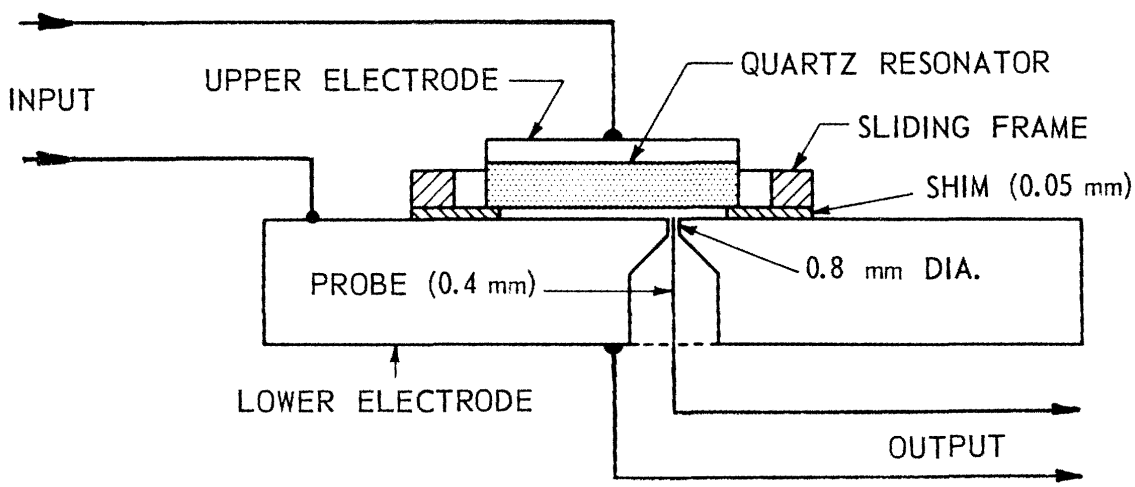


Figure 28. Sketch of the Crystal Probe.

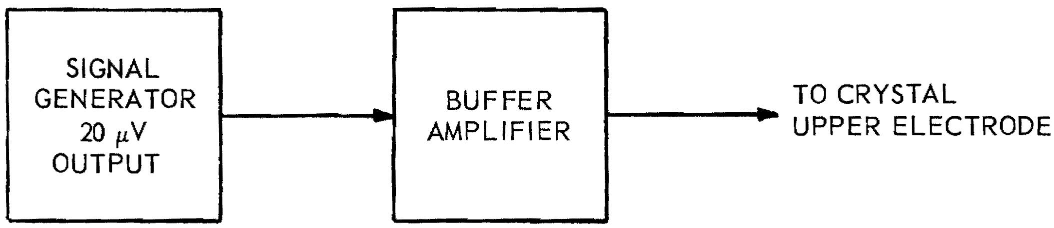
marginal stability for this purpose. Initially, correlation of the polarization patterns with the frequency spectrum was very difficult since provision had not been made for determining the frequency accurately. Later, a Berkeley Model 5570 frequency meter was used to measure the signal generator frequency.

The response of the amplifier-detector system is broad-band; however, the voltage gain is not adjustable. Amplitude scaling of the polarization pattern is accomplished by varying the input to the crystal from the signal generator. Neither the crystal drive voltage nor the crystal power is held constant from trace to trace; the equipment is adjusted for different responses. The signal generator attenuator dial setting is recorded for each measurement run.

The frequency response and output impedance of the buffer amplifier are shown in Figure 29. Since the approximate motional resistance of the crystal can be determined from the spectrum and Figure 26, the crystal drive during a polarization run can be estimated from the signal generator attenuator dial setting and the curves of Figure 29. The maximum available drive power with the present equipment is less than 65 μw.

The amplitude characteristics of the amplifier-detector-recorder system are shown in Figure 30. The estimated crystal drive and these calibration curves provide a measure of the relative degree of crystal polarization at the various responses.

b. Preparation and Selection of Crystal Plates. For the initial spectral response studies, four parent quartz crystals, A, C, D, and E, were chosen. Each of these parent crystals was cut into four crystals with the following specifications.



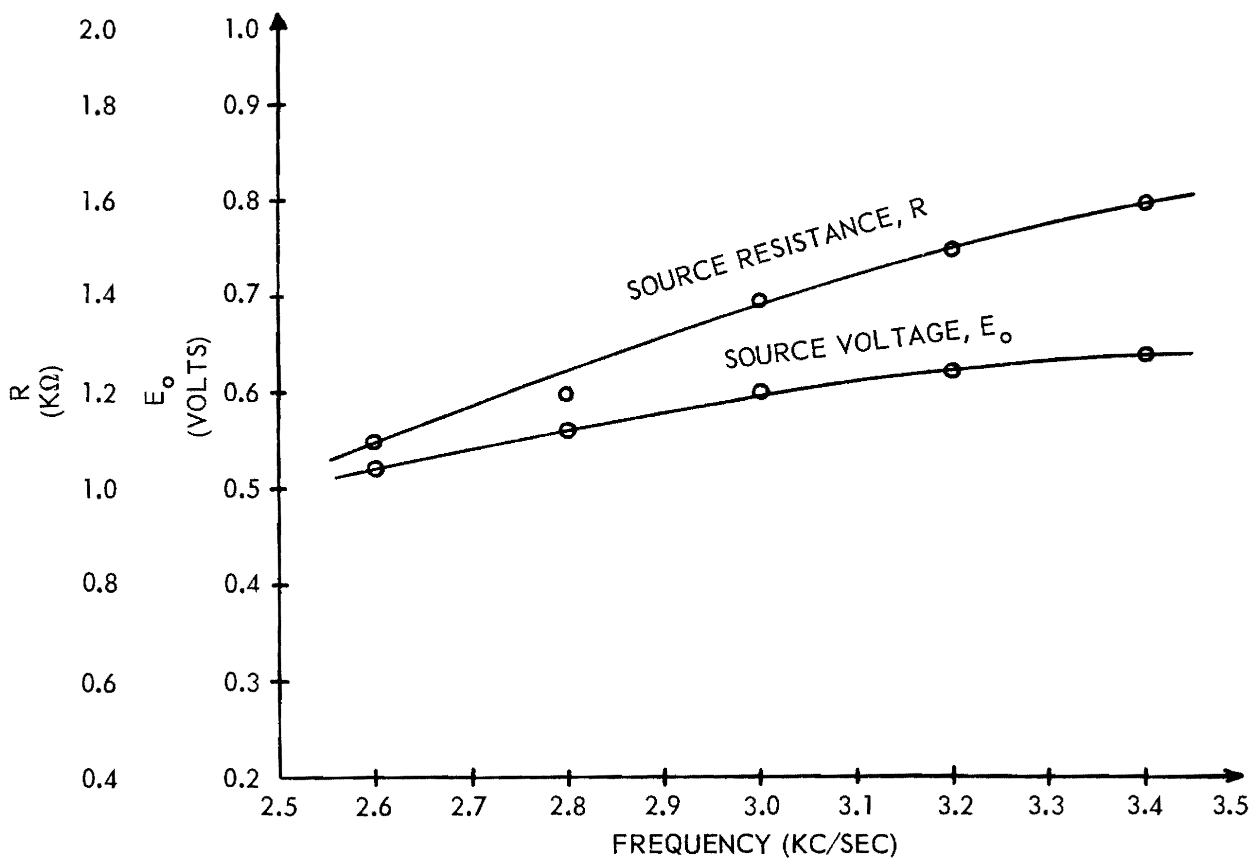


Figure 29. Source Voltage and Source Impedance Characteristics of the Buffer Amplifier.

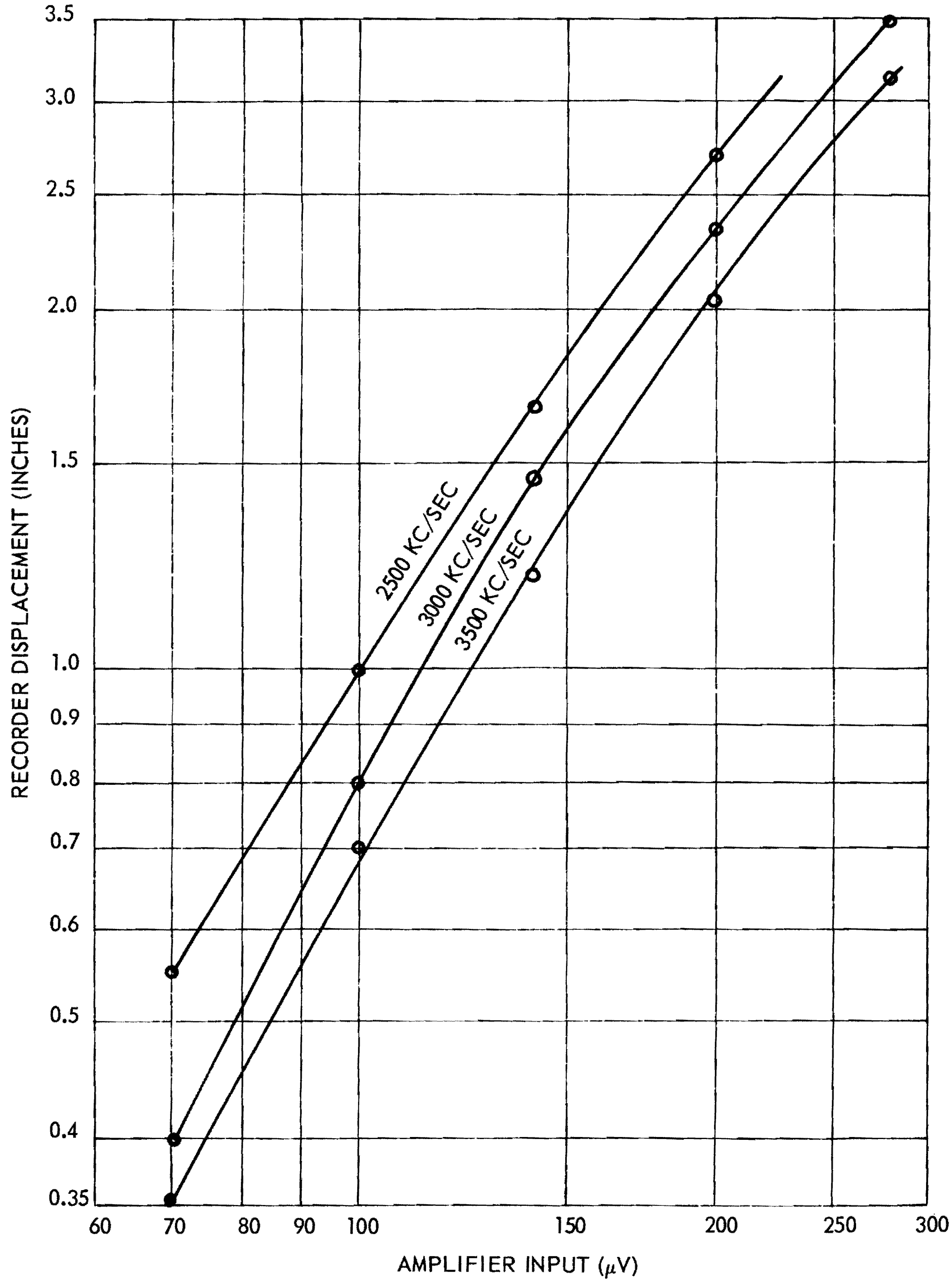


Figure 30. Amplitude Characteristics of the Amplifier-Detector-Recorder System.

Cut: AT at an angle of 35° 15' ± 2'.

Frequency: Third overtone frequency approximately 3022 kc/sec.

Shape: Rectangular, x_o = 24.560 mm ± 0.002 mm

y_o = 1.650 mm ± 0.001 mm

z_o = 27.004 mm ± 0.002 mm

Operational Temperature: Room temperature, 25°C ± 5°C.

Surface: Milky white polish or better.

The angle of cut and direction of the x_o, y_o, and z_o axes are shown in Figure 31. Each of the crystals was numbered A-1, A-2, etc., the letter indicating the parent crystal.

The spectra for all of the crystals were recorded with the equipment which has been described. The two crystals showing the greatest similarity were D-1 and D-2. The high-resolution spectra of these crystals are shown in Figures 32 and 33. The spectra of the other crystals were similar to those of D-1 and D-2. For example, the spectrum of a crystal from a different parent crystal is shown in Figure 34.

Crystals D-1 and D-2 were chosen for the spectrum studies, D-1 for immediate use and D-2 for later use.

c. Mode Chart Preparation. In previous studies, only the relatively strong responses near the frequency of the thickness-shear vibration have been analyzed for AT-cut crystals. The improved resolution of the new equipment has made possible the studies of many of the weak responses. The frequencies of these weak responses can be readily determined from expanded spectrum shown in Figure 32. The wide range spectrum shown in Figure 35 for crystal D-1, is useful in following the stronger responses.

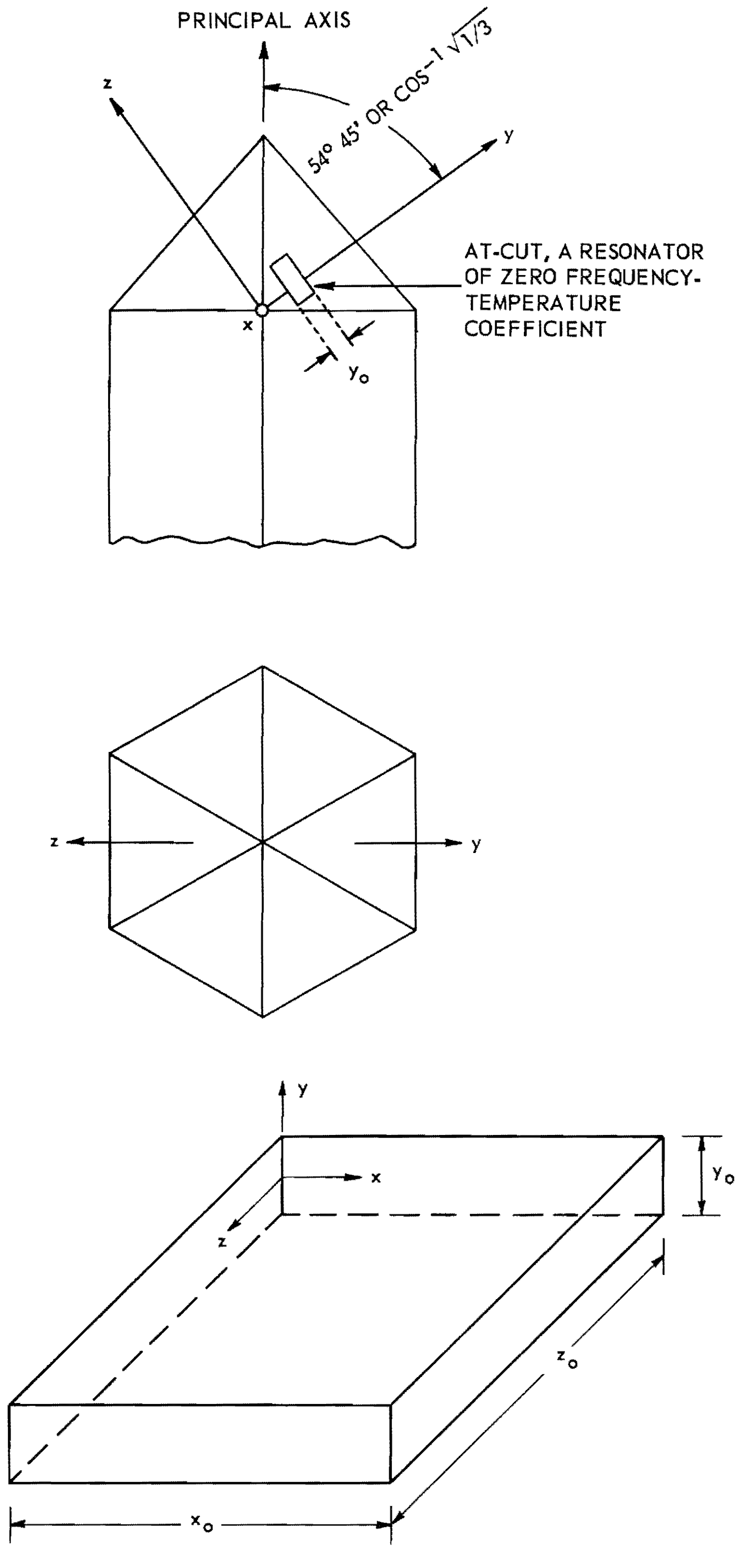


Figure 31. Coordinate Axes of a Rectangular Plate.

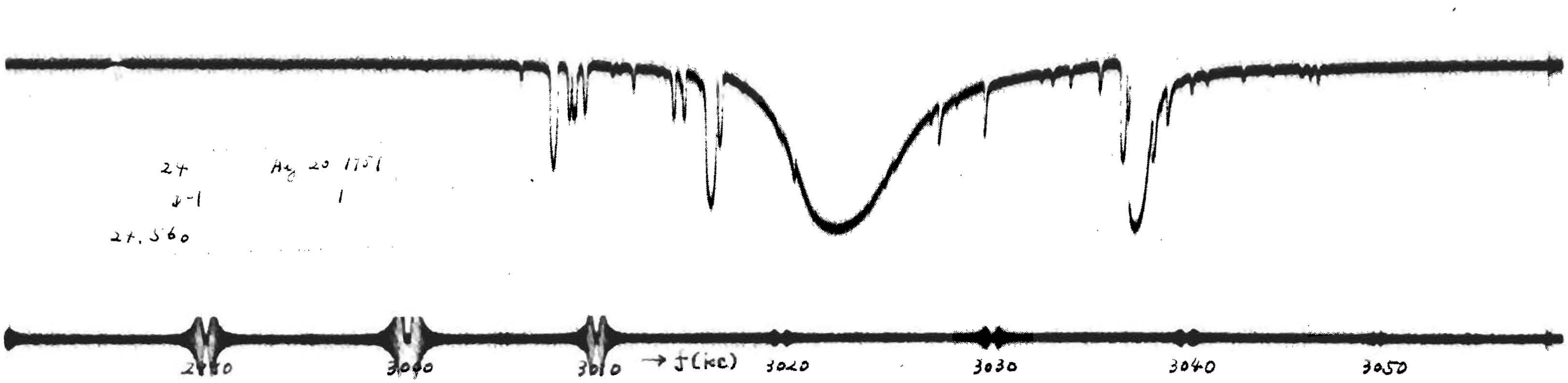


Figure 32. Expanded Spectrum of Crystal D-1.

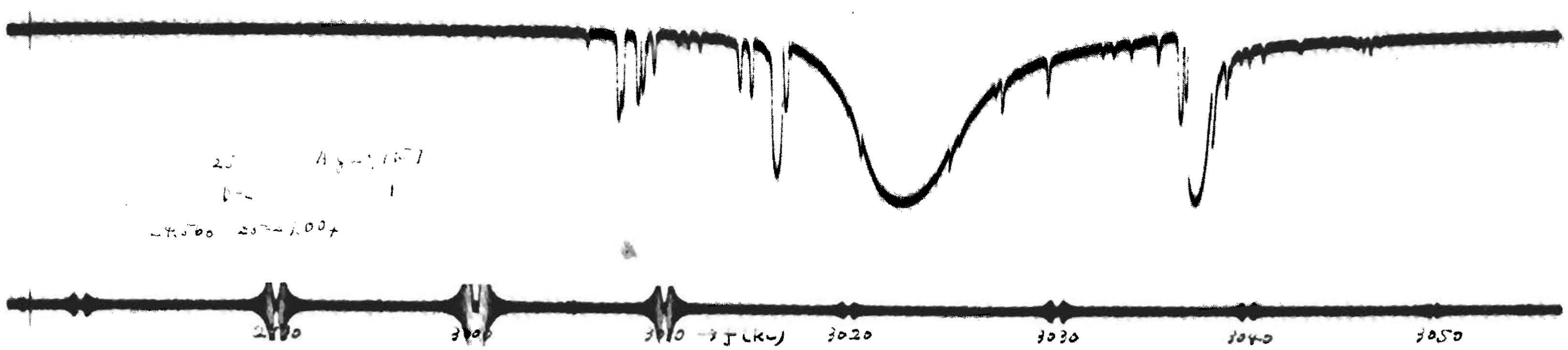


Figure 33. Expanded Spectrum of Crystal D-2.

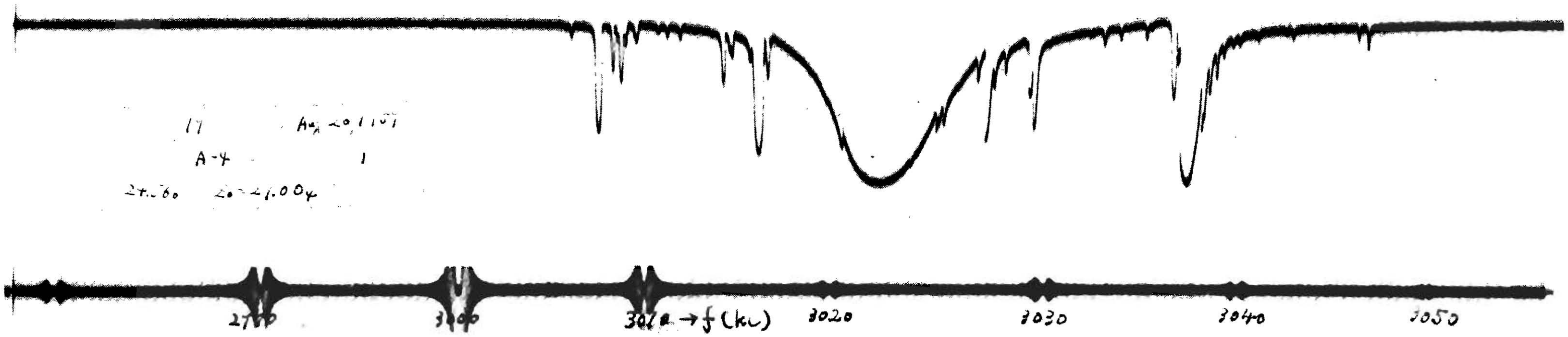


Figure 34. Expanded Spectrum of Crystal A-4.

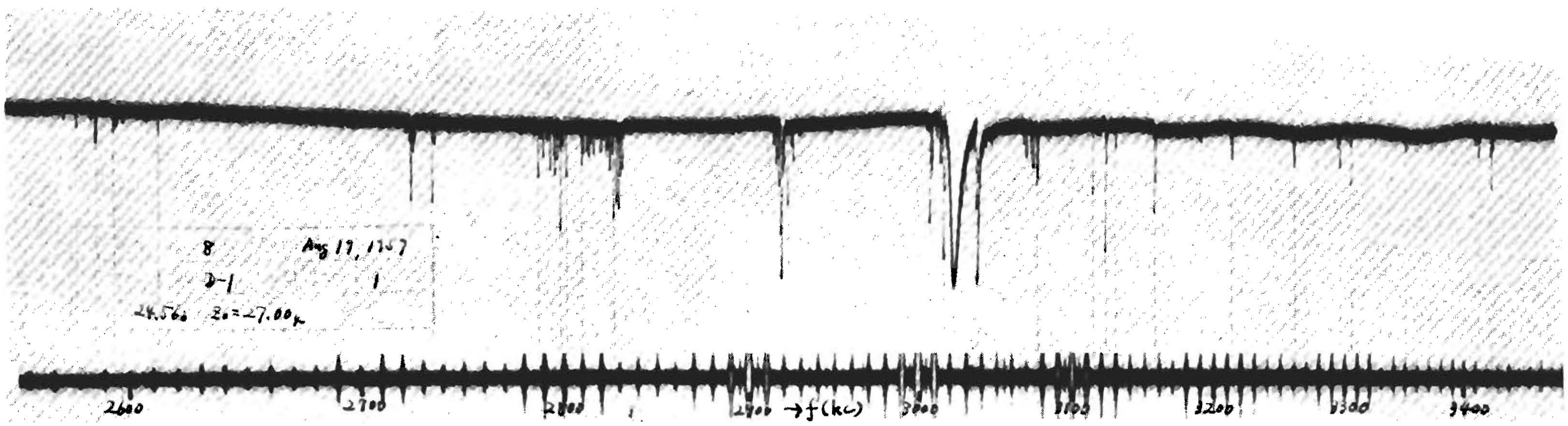


Figure 35. Spectrum of Crystal D-1.

The crystal mode charts are prepared by reducing the x_o dimension of the crystal plate in steps sufficiently small to permit tracing the individual responses. At first, the x_o dimension of crystal D-1 was reduced in steps of 50 microns. This reduction was more than adequate for tracing all of the strong responses; however, it was too large to permit reliable tracing of the smaller responses. The reduction was therefore changed to less than 10 microns per step. A total of 147 reductions have been made with an average step of about 8 microns. Figure 36 shows the mode chart for the weaker responses of crystal D-1. Some of the minor responses cannot be traced through the dimensional reductions. In this figure, the minor divisions in the x_o direction represent 10 microns.

Figure 37 shows the stronger crystal responses as plotted from wide range spectra such as Figure 35. This mode chart is plotted for dimensional reductions of approximately 50 microns per step.

d. Polarization Studies for Mode Identifications. An object of the third overtone study of rectangular crystal plates was to identify and classify the modes of vibration. Many identifications can be made directly from the mode charts as the x_o dimension of the crystal is reduced. Some identifications, however, cannot be assured without additional information concerning the charge distribution on the surface of the plate. This additional information is obtained by means of the probe measurements of the polarization (or charge distribution) with the equipment described previously.

The probe equipment was placed in operation shortly after the spectrum measurements were begun. Polarization patterns for all of the measurable responses of crystal D-1 in the third overtone region were at first recorded.

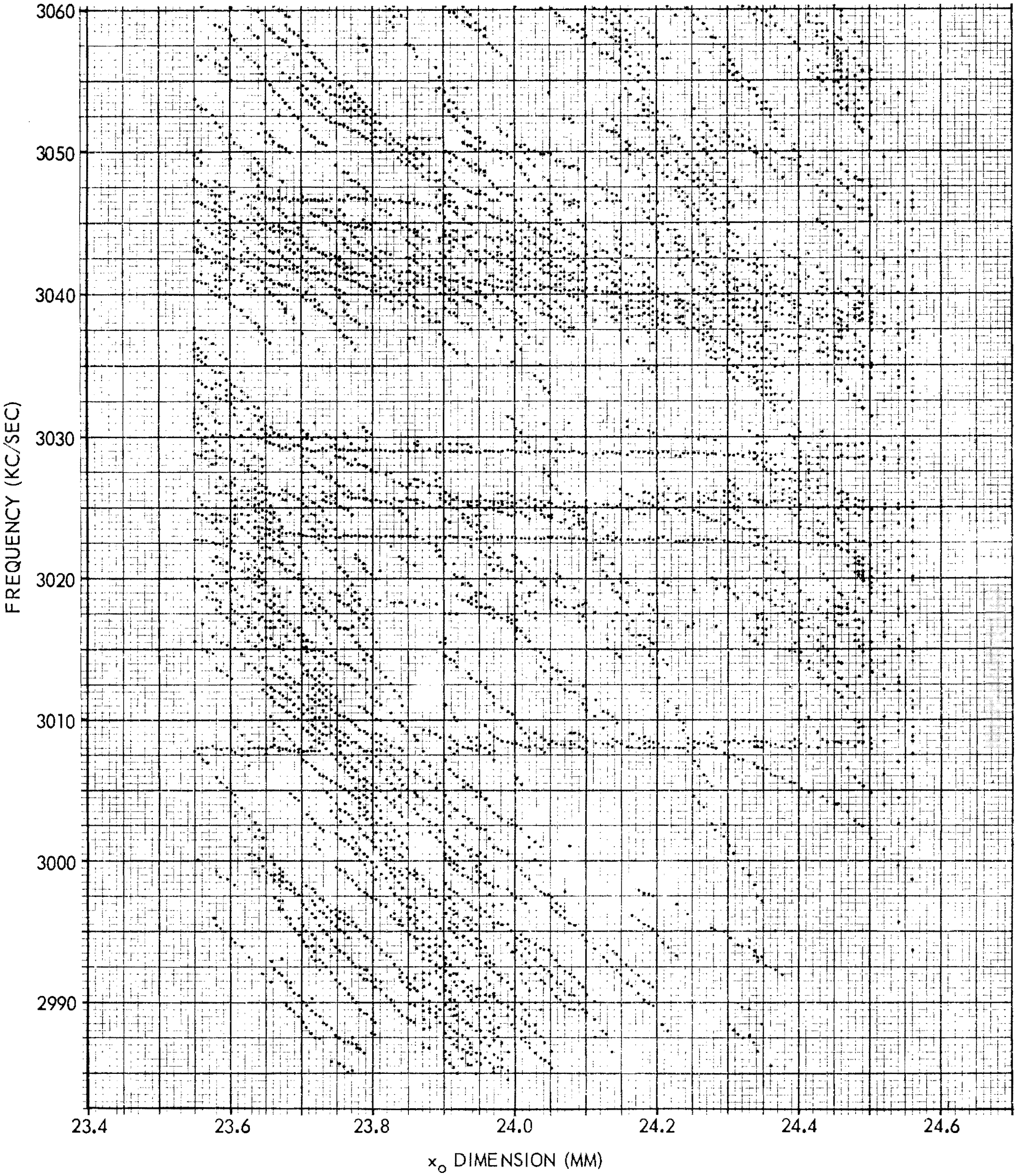


Figure 36. Expanded Mode Chart of Crystal D-1.

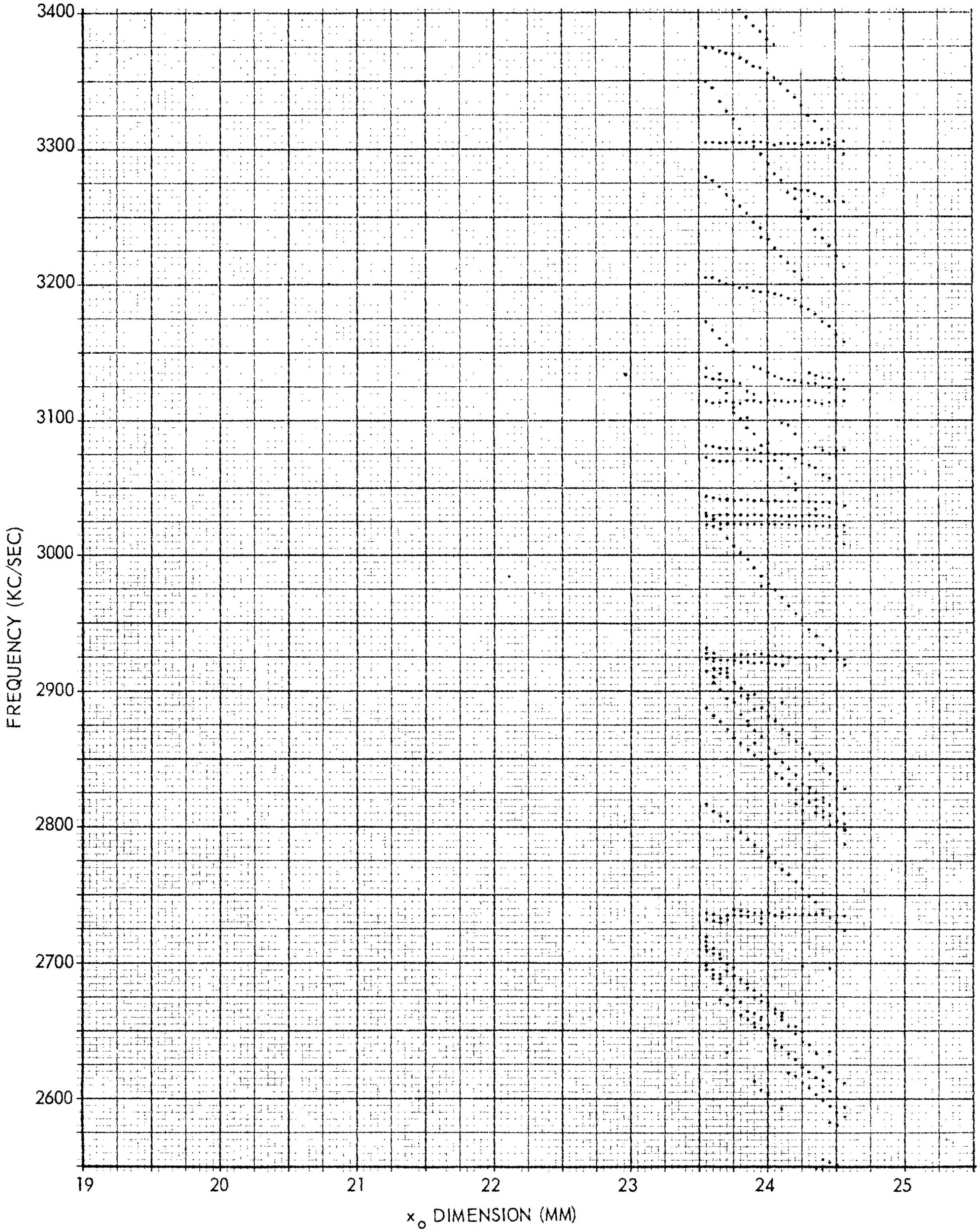


Figure 37. Mode Chart of Stronger Responses of Crystal D-1.

Many of the vibrational mode identifications were verified from these initial polarization measurements. Throughout the remaining process of reducing the x_o dimension of the crystal, polarization records of questionable modes were made. After a mode was definitely identified, only occasional records were made for confirmation of the mode.

Modes are identified according to the number of loops or half-wavelengths of charge distribution which occur respectively in the x_o, y_o, and z_o directions of the crystal plate (see Figure 31). For example, a fundamental thickness-shear vibration would show constant charge in the z_o direction and a single loop in the x_o and y_o directions and would thus be designated the (1,1,0) mode. The third overtone thickness-shear mode still has only one loop in the x_o direction but three loops in the y_o direction and would thus be designated (1,3,0). One of the inharmonic modes is characterized by constant charge in the z_o direction, a number of loops in the y_o direction corresponding to the thickness-shear overtone order, and a number of loops in the x_o direction corresponding to the inharmonic order. For example, the inharmonic series in the region near the fundamental thickness-shear frequency are designated (3,1,0), (5,1,0), (7,1,0), etc., in order of increasing frequency. The inharmonic series near the third overtone of thickness-shear frequency is designated (3,3,0), (5,3,0), (7,3,0), etc., in order of increasing frequency. Other inharmonic series also exist which have non-zero order in the z_o direction (for example (1,3,2)).

The polarization patterns can be measured with the present equipment in the x_o and z_o directions but not in the y_o (thickness) direction. Previous studies and theories have indicated the nature of the standing wave in the y_o direction. Other modes of vibration, however, exist for which the frequency may or may not depend on the x_o dimension. These modes have been classified for convenience according to their frequency dependence and according to their harmonic structure. Four such classes have been observed on the wide-range mode chart.

Type a modes: thickness-shear modes including the fundamental, the overtones of the fundamental, and the corresponding sets of inharmonic series. The frequencies of each of these modes are determined primarily by the y_o dimension (thickness). The frequencies of the fundamental and third overtone are nearly independent of x_o, but the inharmonic modes of increasing order are progressively dependent on x_o, the frequency increasing as x_o is decreased.

Type b modes: flexure modes (or possibly more complicated modes related to flexure) which occur uncomplicated only at frequencies below that of the fundamental. Strong coupling of these modes with the modes of type a at and above the frequencies of the fundamental and the third overtone. To a first approximation, the frequency of a mode of any order varies inversely with the x_o dimension. Even orders only (in loops in the polarization pattern) are present, at relatively close spacing in frequency between orders.

Type c modes: face-shear modes depending only on the x_o dimension. The frequency varies, to a good approximation, inversely with x_o. Odd orders are present at spacing in frequency between orders (odd only) roughly twice the spacing of the b modes.

Type d modes: face-shear modes depending only on the z_o dimension. The frequency is nearly independent of x_o. Odd orders occur at a frequency spacing comparable to the c modes.

The mode chart of Figure 37 has been replotted in Figures 38 and 39 to separate the types a and b modes from the types c and d modes. The type and

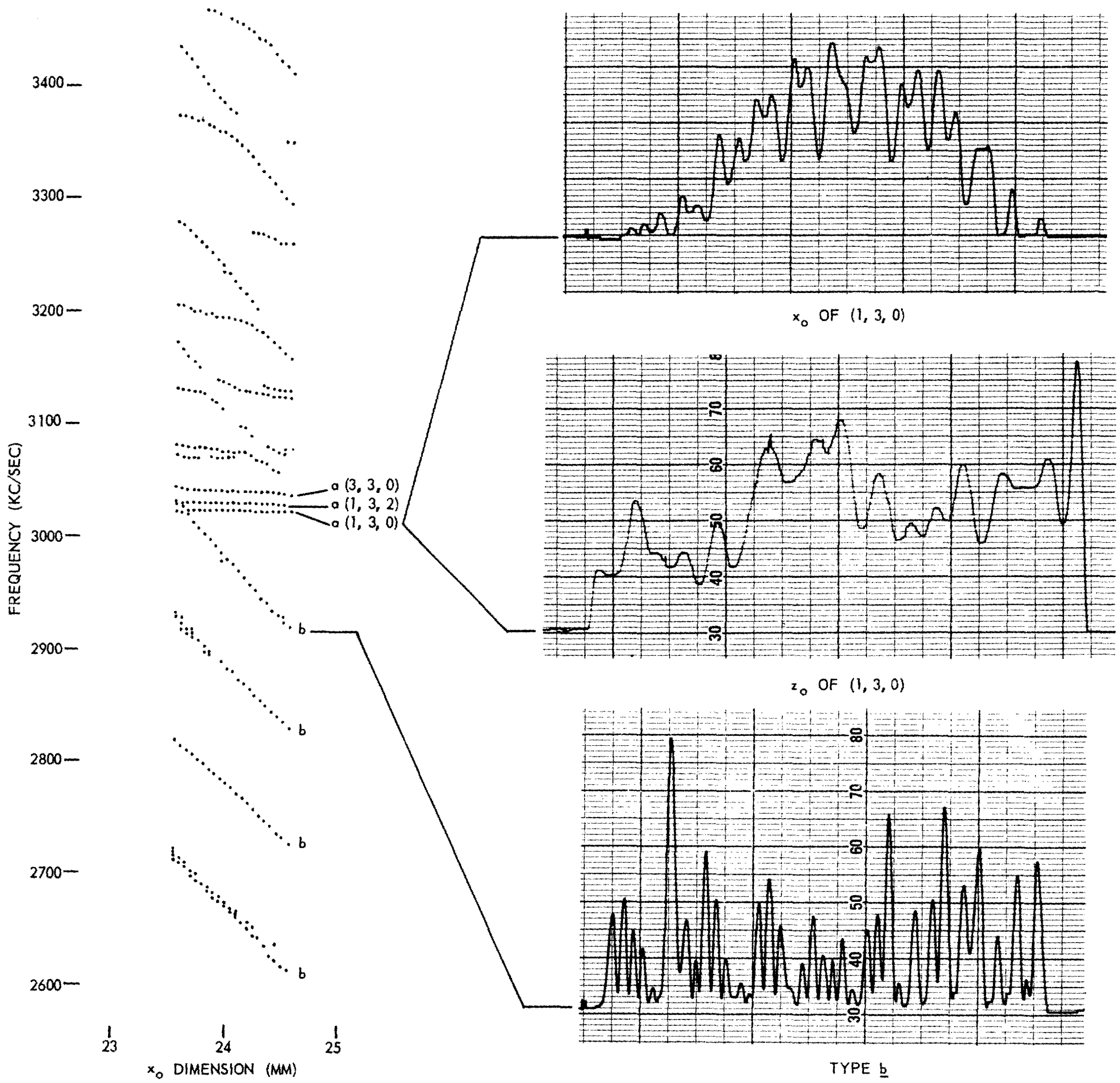


Figure 38. Mode Chart and Sample Polarization Patterns for Types a and b Vibrations.

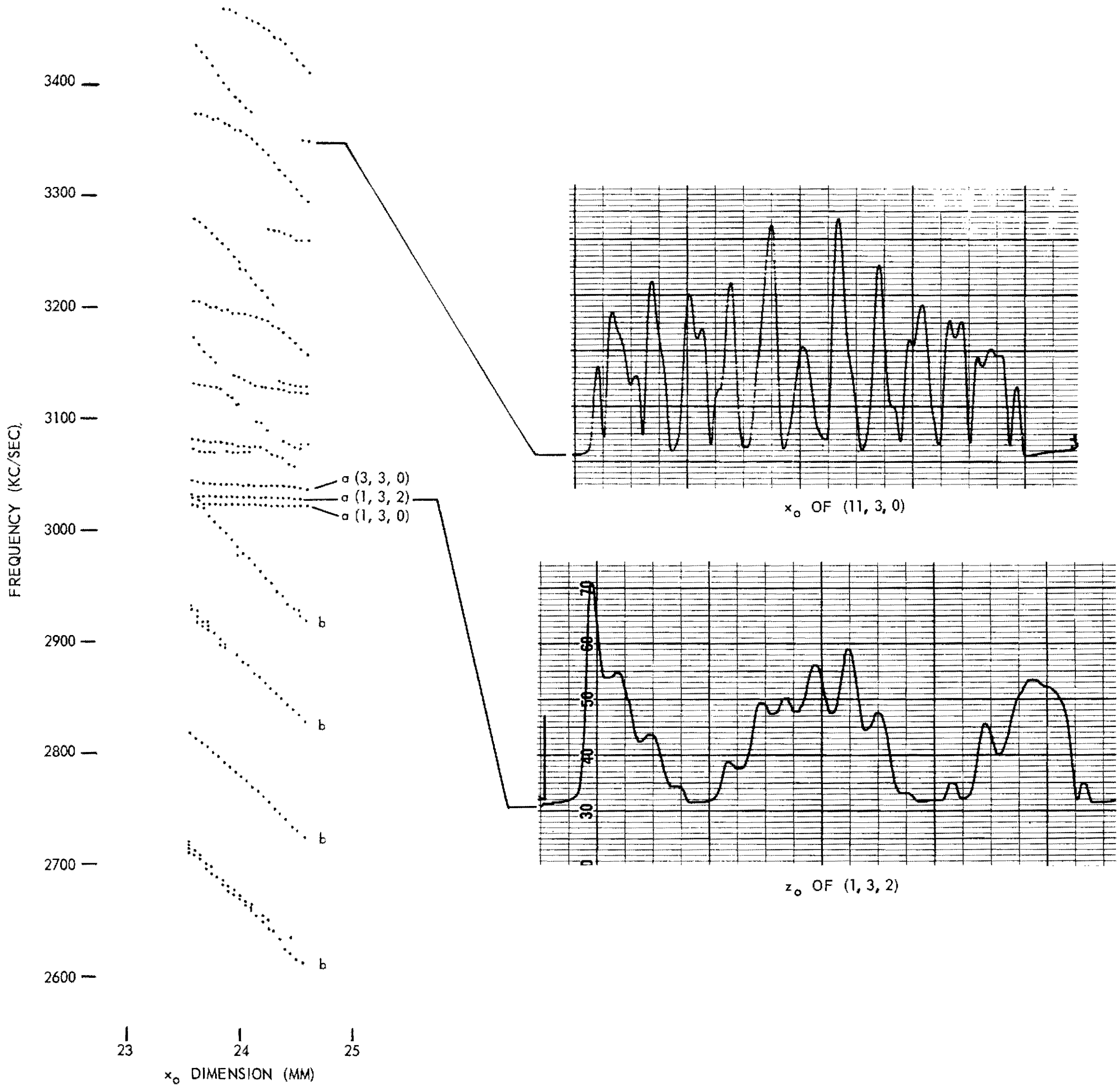


Figure 38 (Continued). Mode Chart and Sample Polarization Patterns for Types a and b Vibrations.

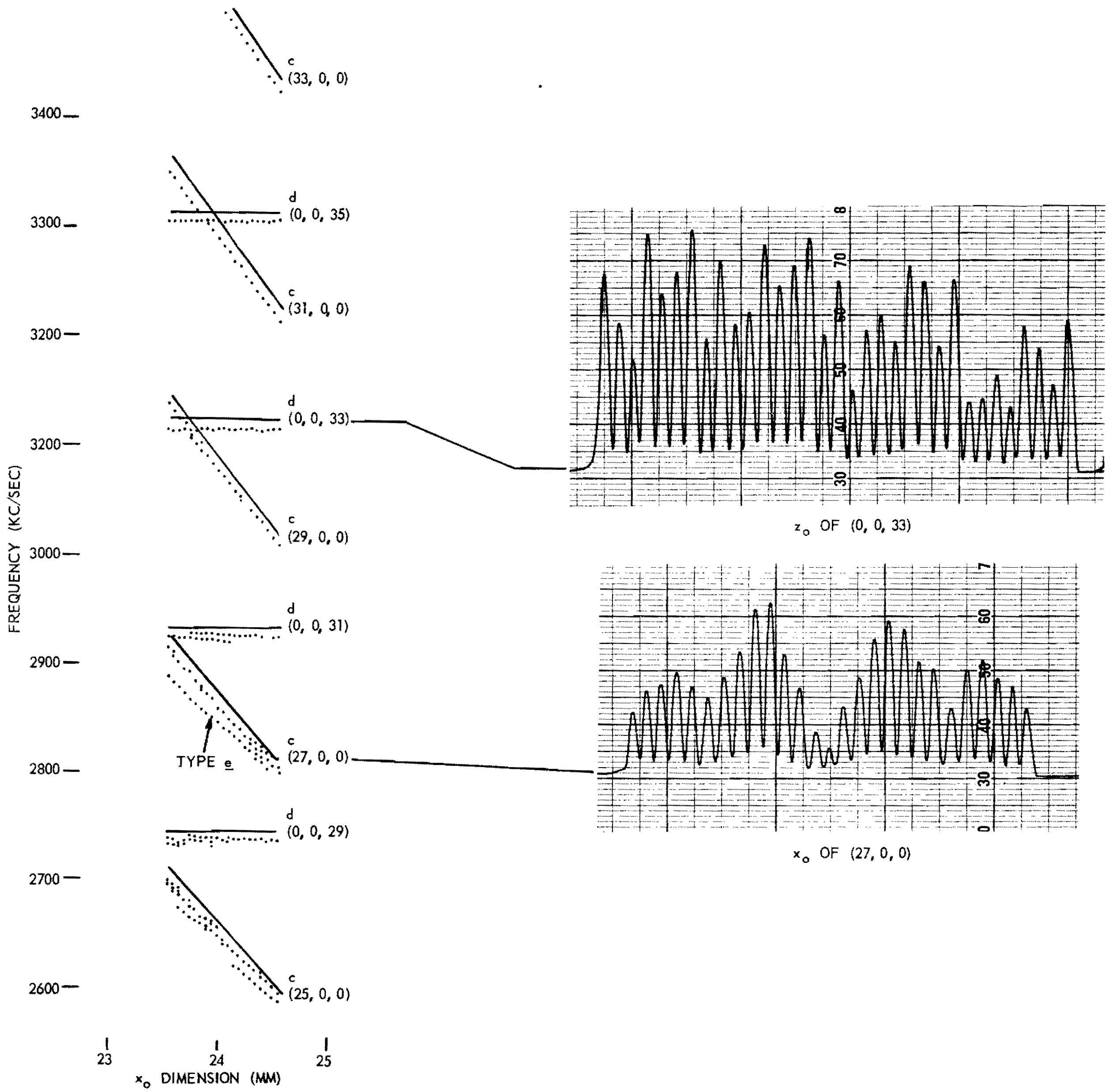


Figure 39. Mode Chart and Sample Polarization Patterns for Types c and d Vibrations.

order of the mode is indicated. The orders of the type b modes have not been determined because of the lack of clarity of the polarization recordings.

Five typical charge distribution patterns are shown in Figure 38. The patterns illustrate to some extent the interference of other modes. Even with severe interference, mode patterns such as the x_o of $(1,3,0)^{\dagger}$ can be readily identified. The z_o of (1,3,0) is actually a constant, that is, all of the variations shown represent interfering modes. Care and intuition assist in arriving at an identification. The z_o of (1,3,0) is more readily identified when it is compared to the z_o of (1,3,2). The one full loop and two half-loops of the latter are easily recognized. The x_o of (11,3,0) represents another case where care must be used in arriving at an identification. Shown also is a charge distribution pattern of a type b mode. Since the interference is severe and the loop count is large, the identification is uncertain.

Figure 39 shows only the types c and d modes. The solid lines represent the calculated frequencies and will be discussed later. The relative absence of coupling between the various modes is obvious in Figure 39. The identifications of modes are, therefore, more readily accomplished. Two typical polarization patterns are shown. The loop count is unmistakable in both cases.

One mode, tentatively designated type e, is marked on the mode chart of Figure 39. The nature of this mode was not determined; however, it obviously cannot belong to either type c or type d because of its frequency position on the mode chart.

The identification of a mode depends upon an agreement among several polarization patterns at different x_o dimensions. Although interference may

† The polarization record taken in the x_o direction centered in the z_o direction for the frequency corresponding to the mode (1,3,0).

reduce the clarity of a pattern at one x_o dimension, other dimensions may usually be found where the patterns are unmistakable. An exception to this generality, as previously noted, is the uncertainty of the order of the type b modes.

e. The Modified Mode Charts and Theoretical Calculations. The wide-range mode chart of Figure 37 shows clearly the stronger modes of crystal D-1. The details of coupling between modes are not shown by this chart, since many of the points represent a grouping of several responses (the resolution of the wide-range spectrum charts is not sufficient to separate the individual responses). Greater detail is available on the section of the chart at expanded scale in Figure 36. However, the points are so numerous even on the expanded chart that individual modes are very difficult to recognize. The modes can be traced more readily when the relative motional resistance of each response is indicated (inversely) by the size of the dot. Figure 40 is a mode chart plotted with the larger points representing all responses with resistance less than 20,000 ohms and with the smaller points representing all responses with resistances between 20,000 ohms and 200,000 ohms. Several of the modes are identified.

Figure 41 shows only the responses with resistances less than 20,000 ohms. All of the identified modes remain although some of the points of these modes, particularly the (1,3,2), have dropped out. The third overtone thickness-shear response, (1,3,0) is clearly defined in Figure 41. The calculated frequency shown on this figure is from an equation by Koga and others in a recent publication[†] in which it is shown that the resonant frequency, f_q, of the thickness-

[†] I. Koga, M. Aruga, and Y. Yoshinaka, "Theory of Plane Elastic Waves in a Piezoelectric Crystalline Medium and Determination of Elastic and Piezoelectric Constants of Quartz," Physical Review 109, No. 5, pp. 1467-73 (March 1958).

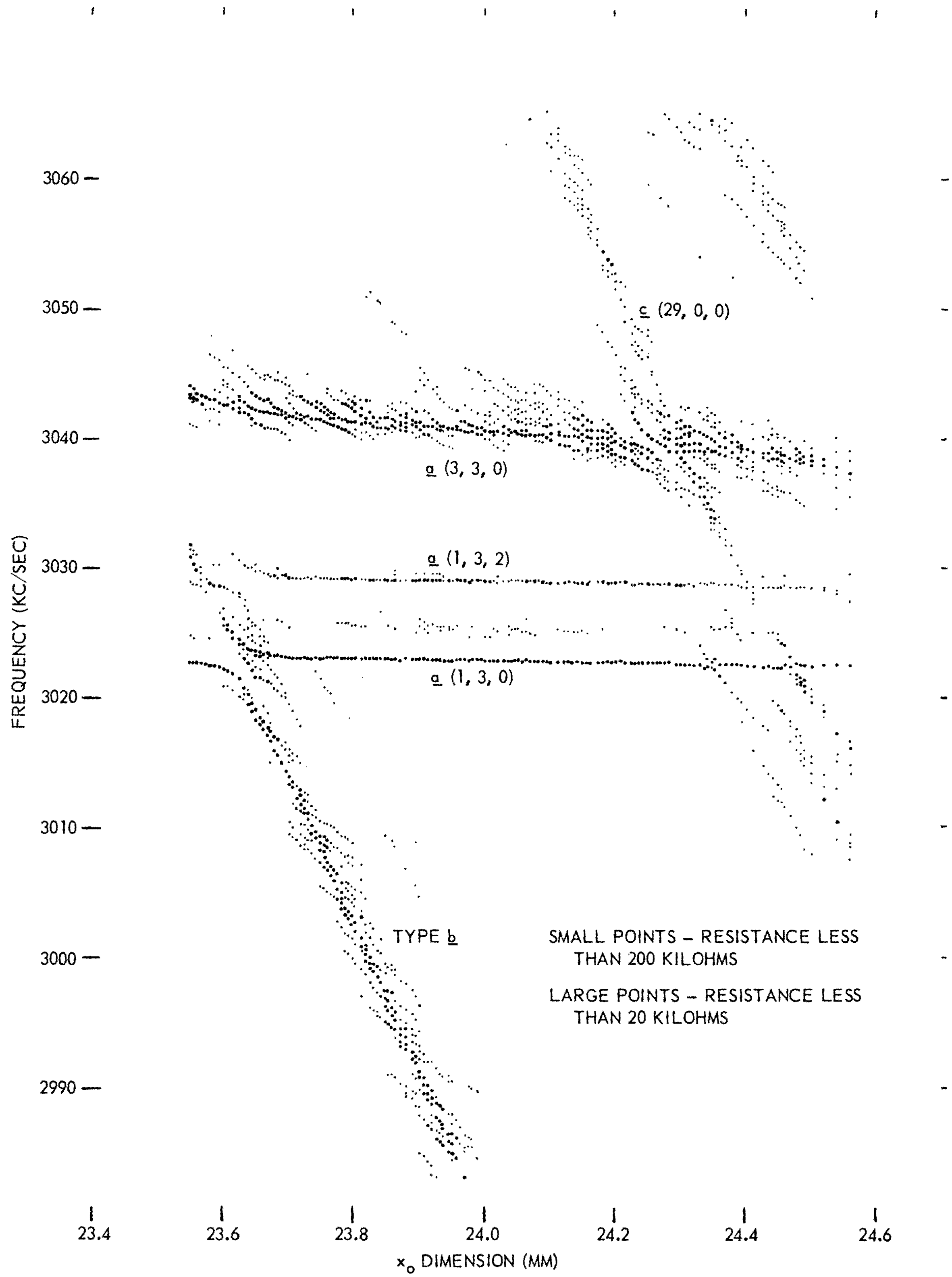


Figure 40. Expanded Mode Chart with Resistance Classification.

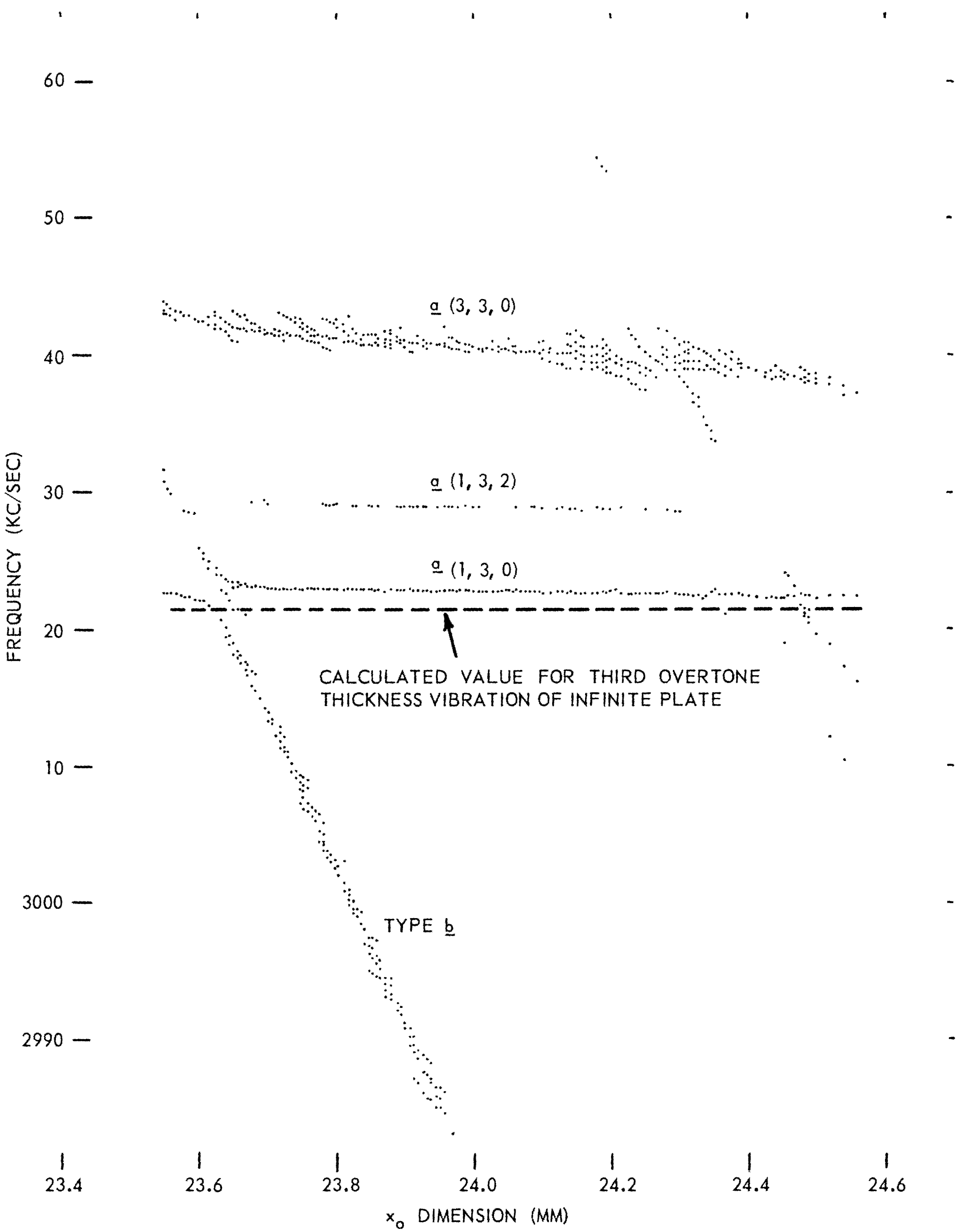


Figure 41. Expanded Mode Chart: Responses with Resistance Less Than 20 Kilohms.

shear vibration of a high harmonic order, q, of a quartz plate of thickness y_o and of infinite extent in x_o and z_o satisfies the relation

$$\lim_{q \to \infty} \frac{f_q}{q} = \frac{1}{y_o} \sqrt{\frac{c}{4\rho}} \qquad (1)$$

where, for an AT-cut plate,

$$\frac{c}{4\rho} = m^2 \frac{c_{66}}{4\rho} + n^2 \frac{c_{44}}{4\rho} + 2mn \frac{c_{14}}{4\rho} + m^2 \frac{1}{4\rho} \frac{4\pi}{K} (m\epsilon_{11} + n\epsilon_{14})^2 \qquad (2)$$

in which

$$m = \sqrt{\frac{2}{3}} \qquad (3)$$

and

$$n = \sqrt{\frac{1}{3}} . \qquad (4)$$

The numerical values of the elastic and piezoelectric constants are

$$\begin{aligned}
\frac{c_{66}}{4\rho} &= 3.7632 \times 10^{10} \text{ cm}^2/\text{sec}^2, \\
\frac{c_{44}}{4\rho} &= 5.49861 \times 10^{10} \text{ cm}^2/\text{sec}^2, \\
\frac{c_{14}}{4\rho} &= -1.70501 \times 10^{10} \text{ cm}^2/\text{sec}^2, \\
\frac{1}{4\rho} \frac{4\pi}{K} \epsilon_{11}^2 &= 0.0728 \times 10^{10} \text{ cm}^2/\text{sec}^2, \\
\frac{1}{4\rho} \frac{4\pi}{K} \epsilon_{14}^2 &= 0.0040 \times 10^{10} \text{ cm}^2/\text{sec}^2, \\
\frac{1}{4\rho} \frac{4\pi}{K} \epsilon_{11} \epsilon_{14} &= -0.01696 \times 10^{10} \text{ cm}^2/\text{sec}^2.
\end{aligned} \qquad (5)$$

The substitution of (3), (4), and (5) into (2) gives

$$\frac{c}{4\rho} = (2.7342 + 0.0225) \times 10^{10}\ \mathrm{cm}^2/\mathrm{sec}^2, \text{ or} \tag{6}$$

$$= 2.7567 \times 10^{10}\ \mathrm{cm}^2/\mathrm{sec}^2. \tag{7}$$

The first constant of (6) is obtained from the first three constants of (5) and represents a mechanical restoring force due to a strain. Normally, these are the only terms which are considered. The piezoelectric restoring force due to a strain, represented by the second constant of (6), is not negligible. It is derived from the last three constants of (5).

The indicated agreement is good despite the relatively low value of $q = 3$ and the accuracy with which the thickness of the crystal plate was measured. By micrometer measurements, the thickness of crystal D-1 was determined to be less than 1.651 but greater than 1.648 mm. More recently the thickness, compared by a sensitive dial gauge with gauge blocks, was found to be 1.6485 ± 0.003 mm. The frequency calculated from this measurement is 3021.5 kc/sec.

The orders of the type b modes are still unknown and no relation for the calculation of frequencies is available.

The type c and d vibrations have been identified as face-shear modes. Equation (1) may be adapted to these modes by the use of the harmonic order p in the x-direction or r in the z-direction. The accuracy is limited, however, by the small dimension in the y-direction (in terms of the wavelength in the x- or z-direction respectively). For the type c and type d modes we have, respectively,

$$f_p = \frac{p}{x_o}\sqrt{\frac{c}{4\rho}} \tag{8}$$

and

$$f_r = \frac{r}{z_c}\sqrt{\frac{c}{4\rho}} \ . \tag{9}$$

From previous work,[†] $c/4\rho$ has been shown to be the single term $c_{55}/4\rho$ with the value of 6.528.

The solid lines of Figure 39 were calculated from (8) and (9). Each line shows good agreement with the corresponding measured points. The polarization patterns have assured that the proper harmonic orders have been selected.

6. Effects of Electrode Diameter on Circular Crystal Plate Responses

a. General. During January 1960, the third overtone measurements of rectangular crystal plates were interrupted to prepare the necessary equipment for a special study of circular crystal plates requested by USASRDL. The purpose of the special study was to determine the effects of electrode diameter on the motional parameters of crystal plates.

b. Modification of Equipment. The crystals chosen for this study were 3-mc/sec fundamental units. As indicated in Figure 26, the change of tap on coil B of Figure 24 displaces the steep part of the curve so that better resolution is available in the resistance range of interest. The half-coil (50%) tap was used for these units.

[†] Koga and others, Quartz Crystal Studies and Measurements, Quarterly Report No. 1, Contract No. DA-36-039 SC-78910, Engineering Experiment Station of the Georgia Institute of Technology, Atlanta, 1 November 1958, pages 24-26 and Appendix B.

The mechanical features of the crystal transport for the measurement of polarization required that the crystal plates be not greater than 28 mm in diameter. A set of electrodes ranging from 3 to 24 mm in diameter in steps of 3 mm and a 28-mm electrode were prepared. (A similar set of square electrodes was prepared for a contemplated study of square crystal plates.) The sliding frame of the probe mount was modified to accept the 28-mm square and circular crystals.

Early studies with the reduced electrode sizes indicated a necessary modification of the probe unit. An indication of the charge distribution on the surface of the crystal is obtained only when a conducting electrode is positioned above the probe to complete the probe circuit.

Since the backup electrode must remain above the probe at all times and since the crystal plate with the main upper electrode in position must traverse the probe, the main electrode must slide under the backup electrode. The main upper electrode of the desired size was therefore evaporated onto the crystal and a circular backup electrode 3 mm in diameter was mounted so that the position opposite the probe is maintained as shown in Figure 42. The evaporated main electrode, 0.3 micron thick, does not interfere mechanically with the backup electrode. A set of plating masks 0.250 inches to 0.875 inches in diameter in steps of 0.125 inches was prepared.

The optimum size of the backup electrode is a compromise between an electrode large enough for the probe to indicate the true charge and still small enough to avoid distrubance of the charge distribution of the small centered electrode. The diameter was chosen at 3 mm, nearly six times the thickness of the crystal. The error introduced by the limited size is estimated (from measurements for this purpose) to be less than 10 percent.

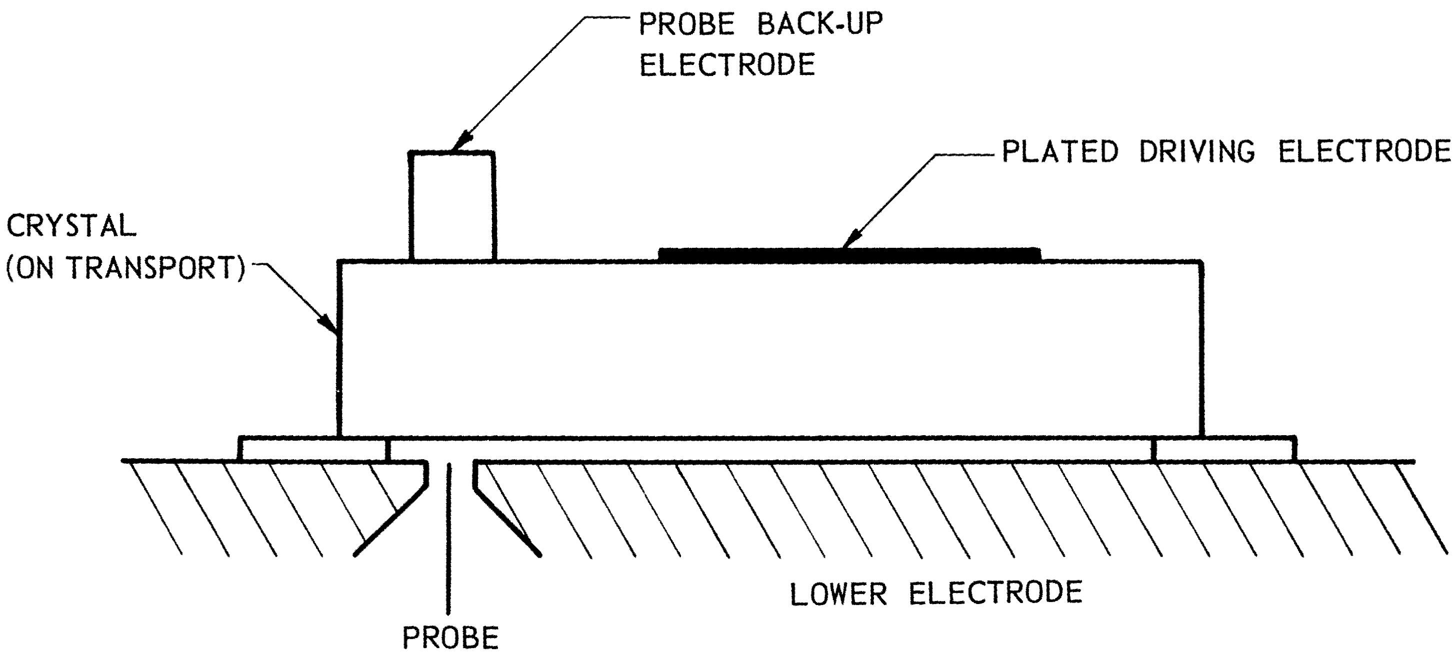


Figure 42. Sketch of the Probe Modification.

Further studies of the probe measurement methods indicated that the changing position of the backup electrode (and the changing shunt capacitance across the crystal plate) resulted in a small shift of the crystal resonant frequency, sufficient to introduce an intolerable deviation of the polarization response. Thus, measurement of the charge distribution requires that the frequency of the signal source of Figure 27 must be adjusted as the backup electrode moves across the crystal. This frequency variation was accomplished automatically by replacing the signal generator and buffer amplifier by an oscillator controlled in frequency by the crystal under test. The requirements that the oscillator circuit have one terminal of the crystal at ground potential and that the crystal must be operated at series resonance were met by the circuit of Figure 43. The oscillator is a Hartley configuration with a separate cathode winding instead of a tap on the grid inductance. Degeneration is provided at all frequencies except crystal resonance because the crystal is in series with the cathode winding. The shunt capacitance of the crystal is antiresonated by an inductance across the crystal. A shunt capacitance is used for fine adjustment although a variable inductance would have accomplished the same purpose. Shown also in Figure 43 is a buffer amplifier to isolate the oscillator from the frequency measurement equipment.

c. Unbeveled Crystal Plates. A total of nine unbeveled circular crystal plates with fundamental frequencies of 3 mc/sec and diameters of 28 mm were obtained. Since the x_o and z_o axes of the plates were not marked when the plates were received, the axes were located by polarized light to an accuracy of 5 degrees. X-ray measurements were later used to locate the axes to one degree or less. Two of the plates with similar spectra were chosen for

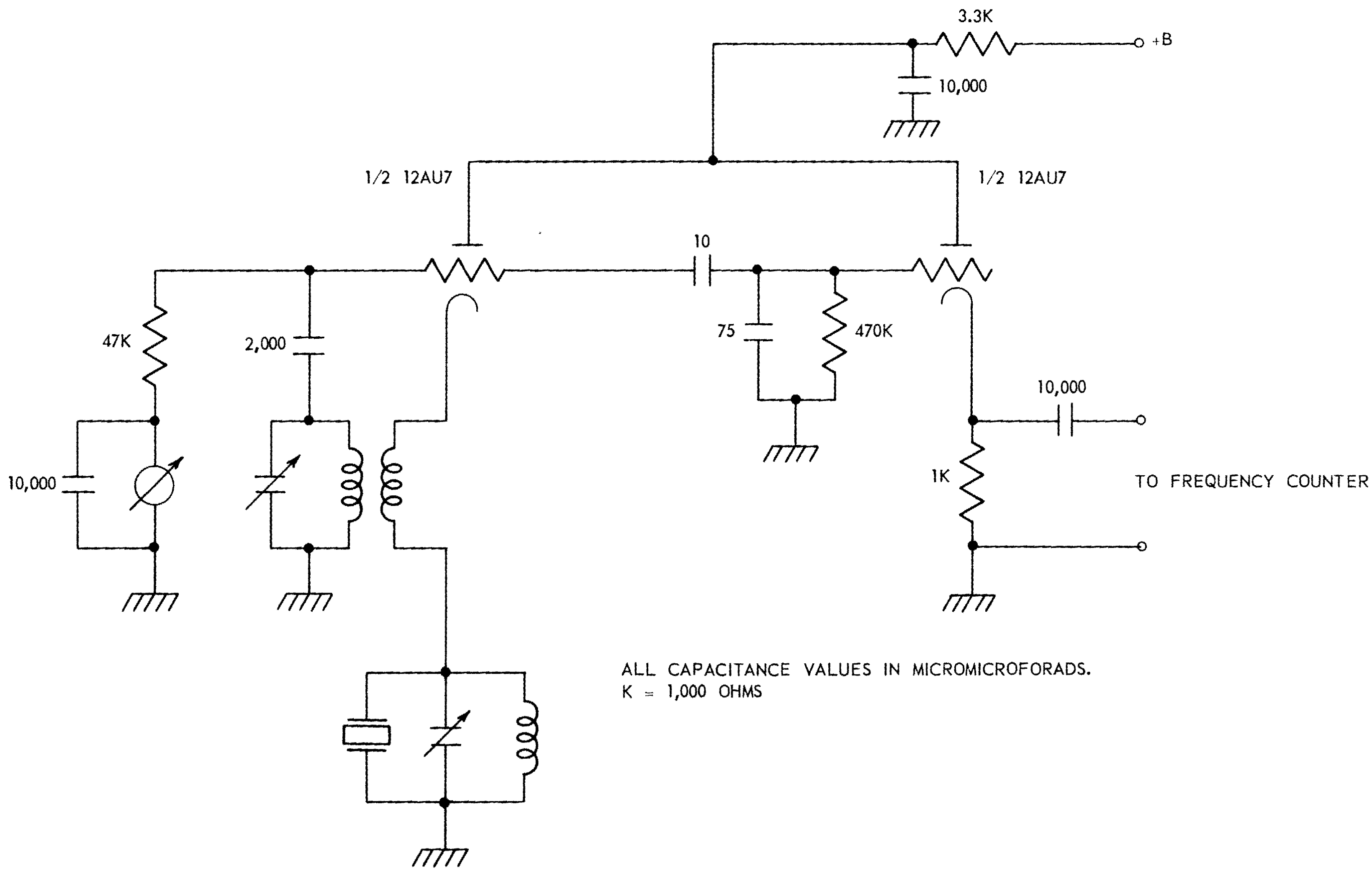


Figure 43. Crystal Controlled Oscillator for Polarization Studies.

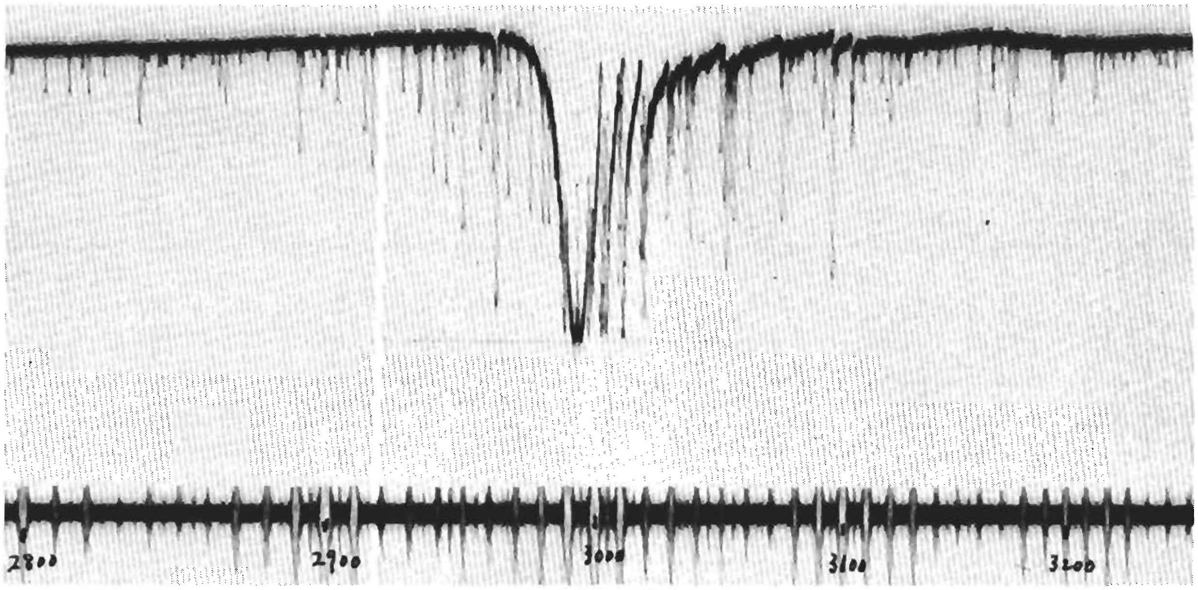
controlled studies. The one designated SC-1 was used for the measurements to be described.

A spectrum of crystal SC-1 was obtained for each upper electrode diameter from 9 to 28 mm. The spectra for the 15- and 28-mm electrodes are shown in Figure 44.

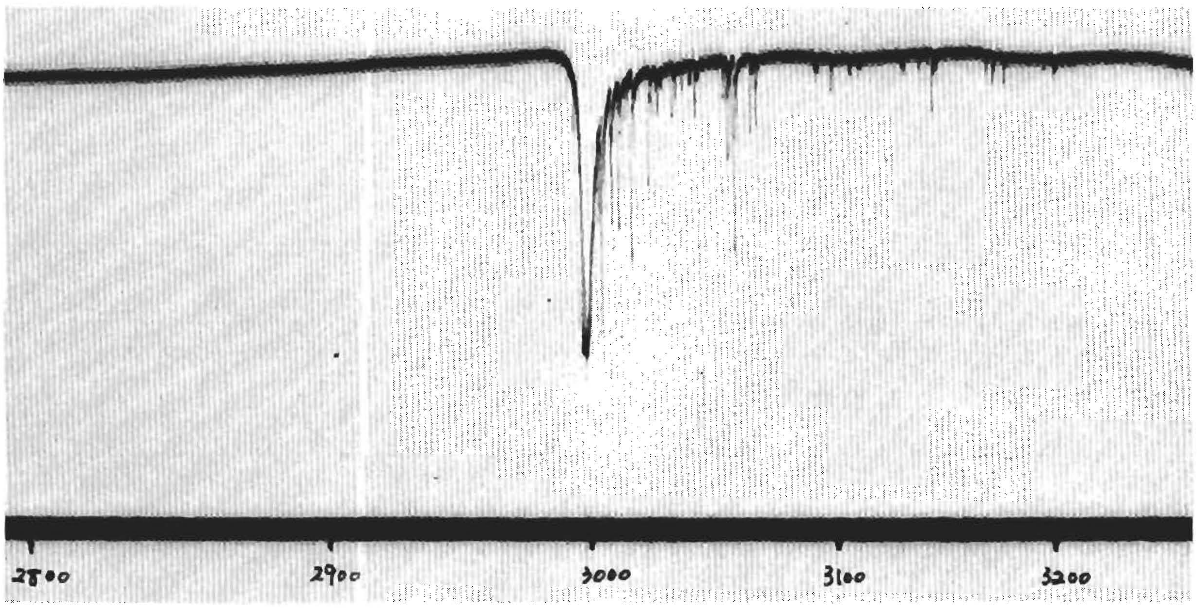
The motional resistance of each response was determined from Figure 44(a) for the stronger responses in the vicinity of the fundamental, as indicated in Figure 45 by the code for the 28-mm electrode (full crystal diameter). The spectra corresponding to the smaller electrodes were then measured and the corresponding resistances derived. The resistance for the response at frequencies below the fundamental with the 24-mm electrode is substantially higher than for the 28-mm electrode (often too high for measurement). At frequencies above the fundamental, however, the change is small and irregular. For the smaller electrodes, 21 mm and 18 mm, this trend continues.

It was evident that the techniques in use were inadequate to follow particular modes with certainty from spectrum to spectrum. Prime interest was shifted at this time to the behavior of the charge distribution with an electrode of reduced size for the fundamental mode. Beveled crystals (with a simpler spectrum) were chosen for this investigation.

d. Beveled Crystal Plates. Four beveled circular plates with specifications otherwise similar to the original nine plates were obtained. One of these designated SCB-2, was chosen on the basis of its freedom from unwanted modes near the fundamental thickness-shear mode.



(a) UPPER ELECTRODE OF 28 mm DIAMETER.



(b) UPPER ELECTRODE OF 15 mm DIAMETER.

Figure 44. Spectra of a Cylindrical Quartz Crystal 28 Mm in Diameter Near the Fundamental Frequency (3 Mc/Sec).

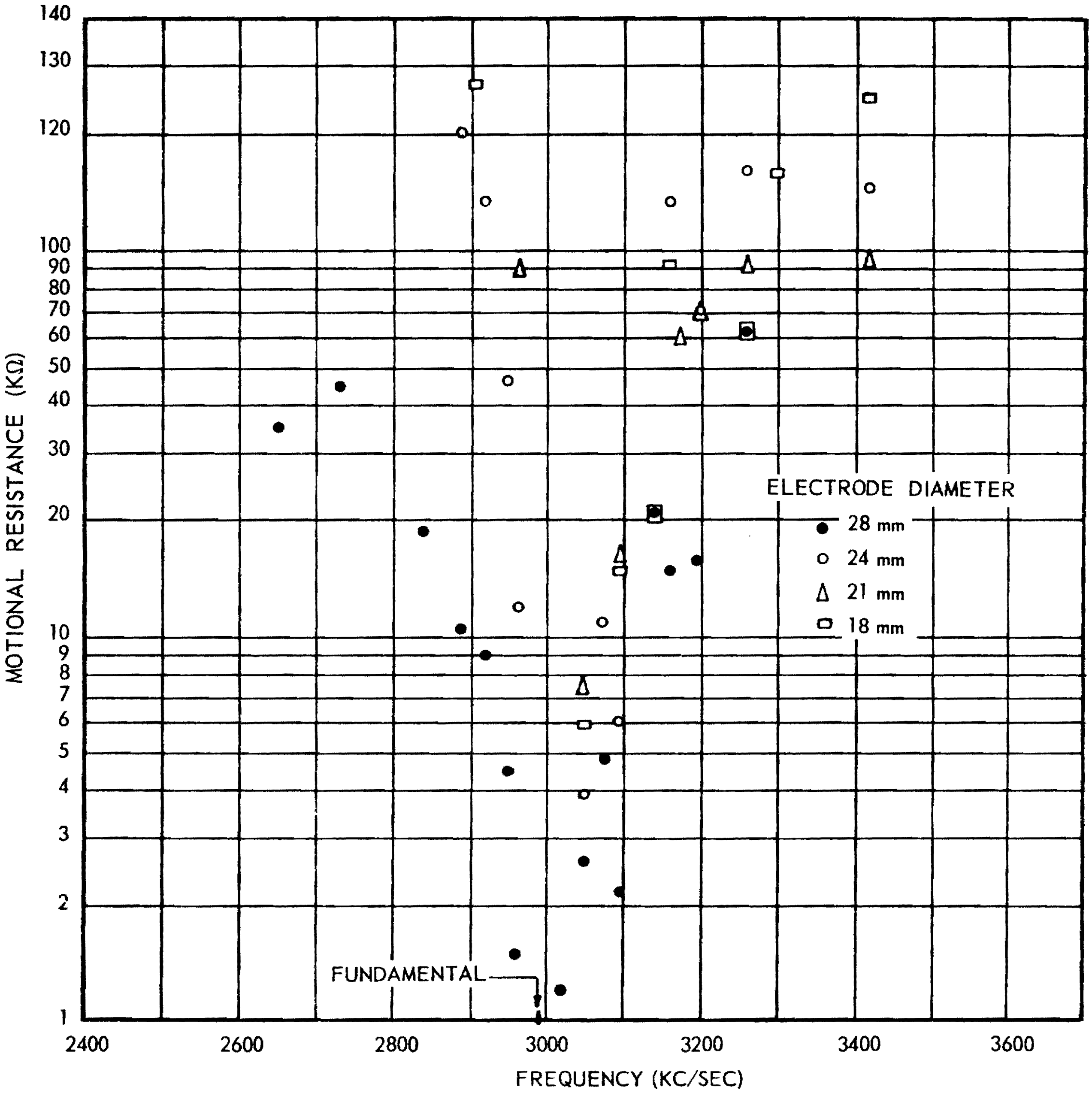


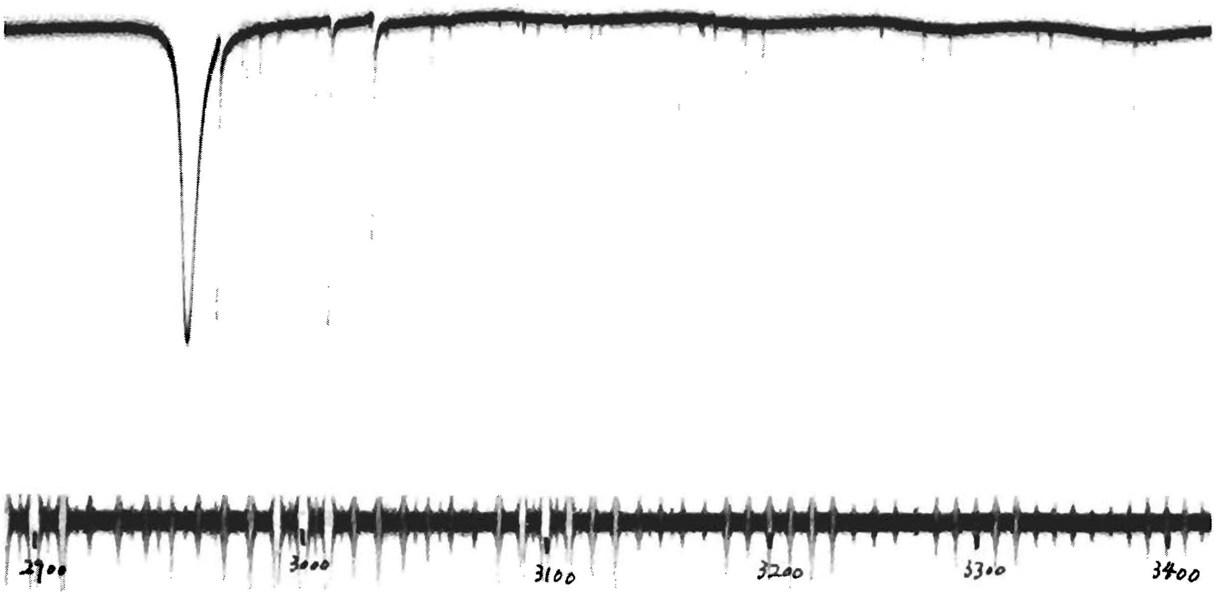
Figure 45. Measured Motional Resistance of the Stronger Responses of an Unbeveled Cylindrical Crystal Near the Fundamental Frequency. THE FREQUENCY OF THE FUNDAMENTAL IS INDICATED: THE RESISTANCE IS TWO ORDERS OF MAGNITUDE BELOW THE LOWER DECADE SHOWN.

A series of spectra was first recorded to determine the accuracy required in centering the small upper electrode. Figure 46 shows spectra for the electrode carefully centered, for the electrode displaced one millimeter in the x_o direction, and for the electrode displaced one millimeter in the z_o direction. The amplitude of some minor responses is affected. The effect on the fundamental frequency and resistance appear, however, to be small. The practice of centering the electrode to within 0.3 mm is believed to introduce no appreciable effect on the fundamental.

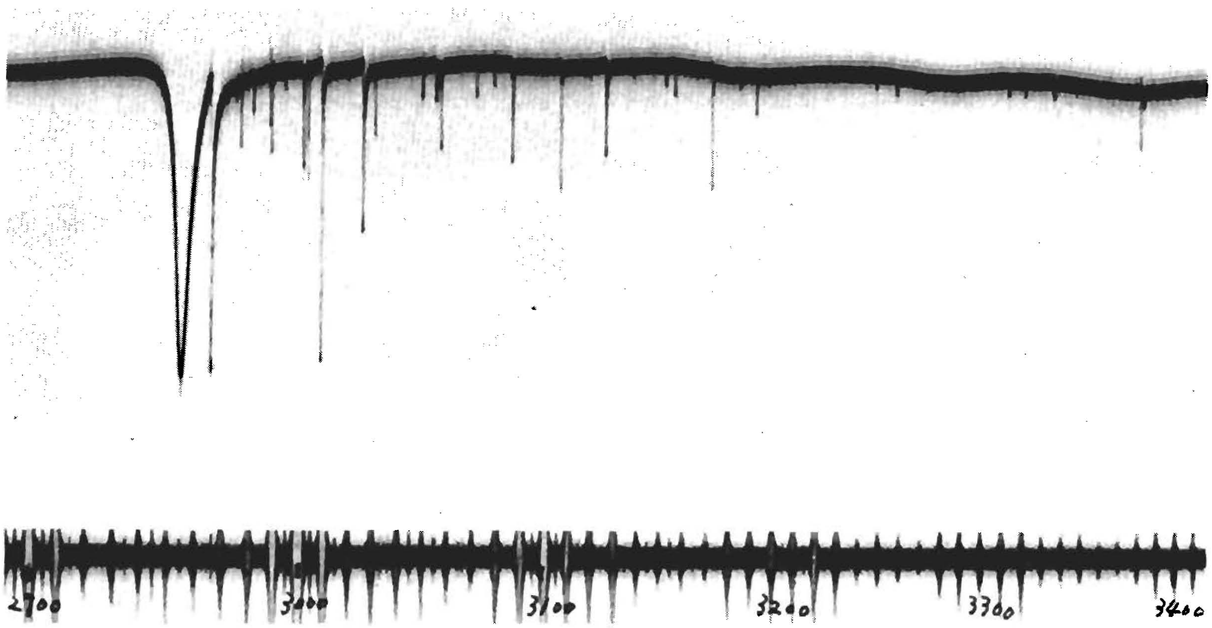
Crystal SCP-2 was used to obtain the spectra for electrode sizes from 28 to 12 mm, shown in Figure 47. The absence of responses below the frequency of the fundamental thickness-shear response is evident. Little change occurs in the spurious modes between the electrode diameters of 28 and 24 mm. At 21 mm, however, a diameter 2 mm less than that of the bevel, a marked decrease in the number of spurious responses occurs. Although further changes in the spectrum are evident for the electrodes of smaller diameter, tentative analysis of the amplitude of particular modes shows no systematic trend as the electrode diameter is reduced.

The fundamental thickness-shear mode of vibration was of primary interest in this investigation. Since the spectrum showed this mode to be free of interference from other modes, this crystal was considered suitable for further study. A series of polarization patterns was obtained for the different electrode diameters at the fundamental frequency.

The effect of the backup electrode on the polarization traces is illustrated in Figure 48 for a main electrode 9.5 mm in diameter. In the record of Figure 48(a), no backup electrode was used. In (b) the backup electrode was connected to the lower crystal electrode and in (c) the backup electrode

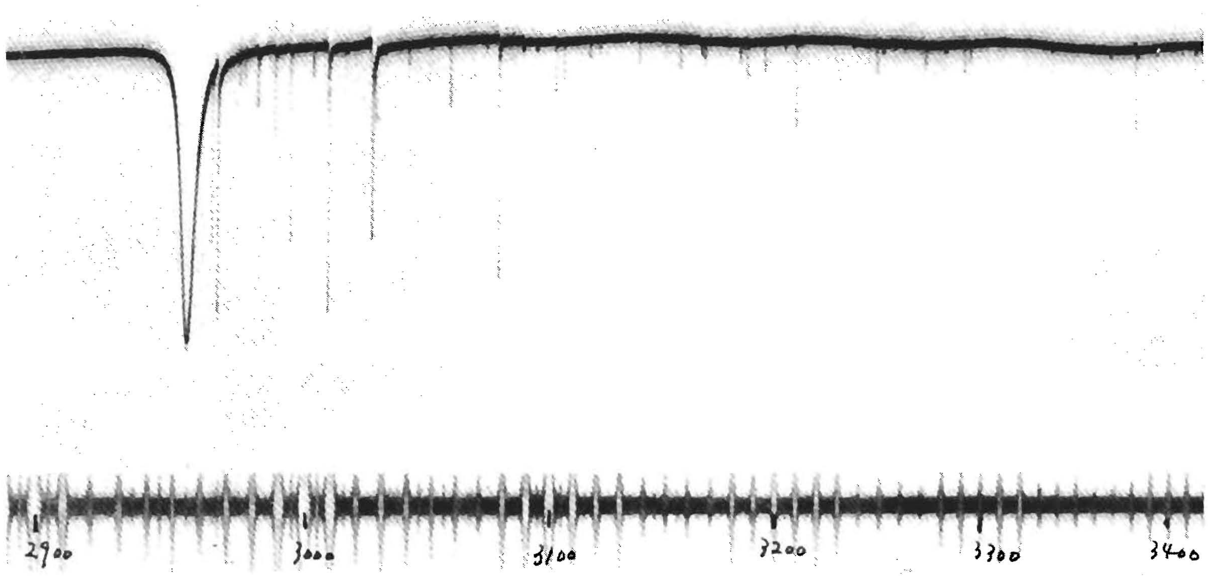


(a) CENTERED UPPER ELECTRODE.



(b) UPPER ELECTRODE DISPLACED 1 mm IN x_0 DIRECTION.

Figure 46. Spectra of Beveled Quartz Crystal with Electrode 15 Mm in Diameter.

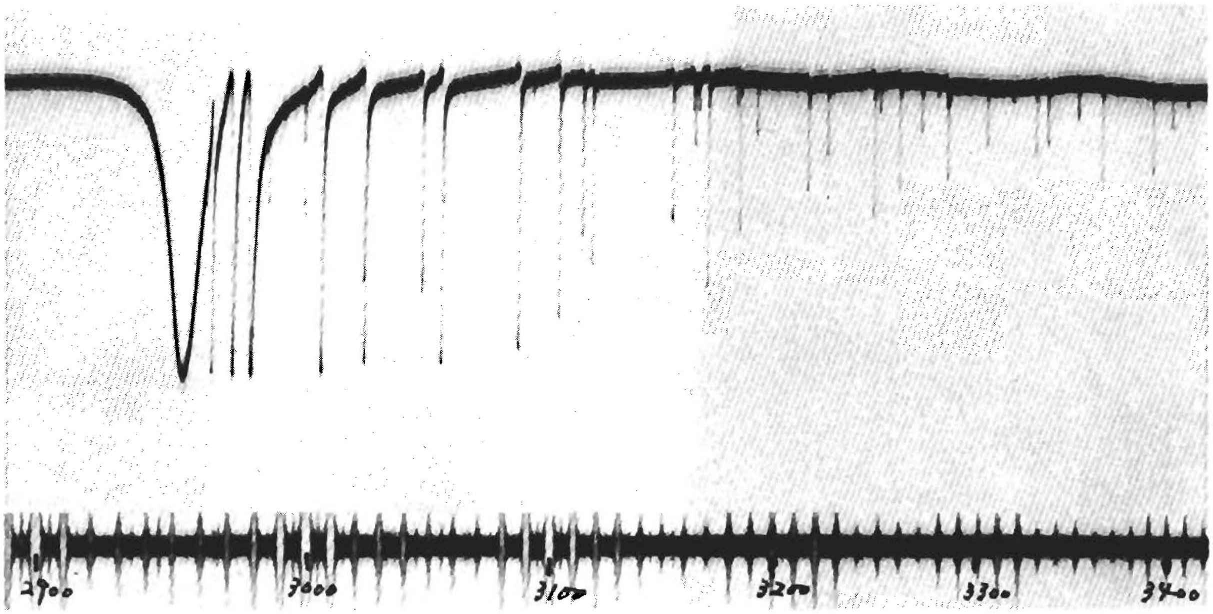


(c) UPPER ELECTRODE DISPLACED 1 mm IN z_0 DIRECTION.

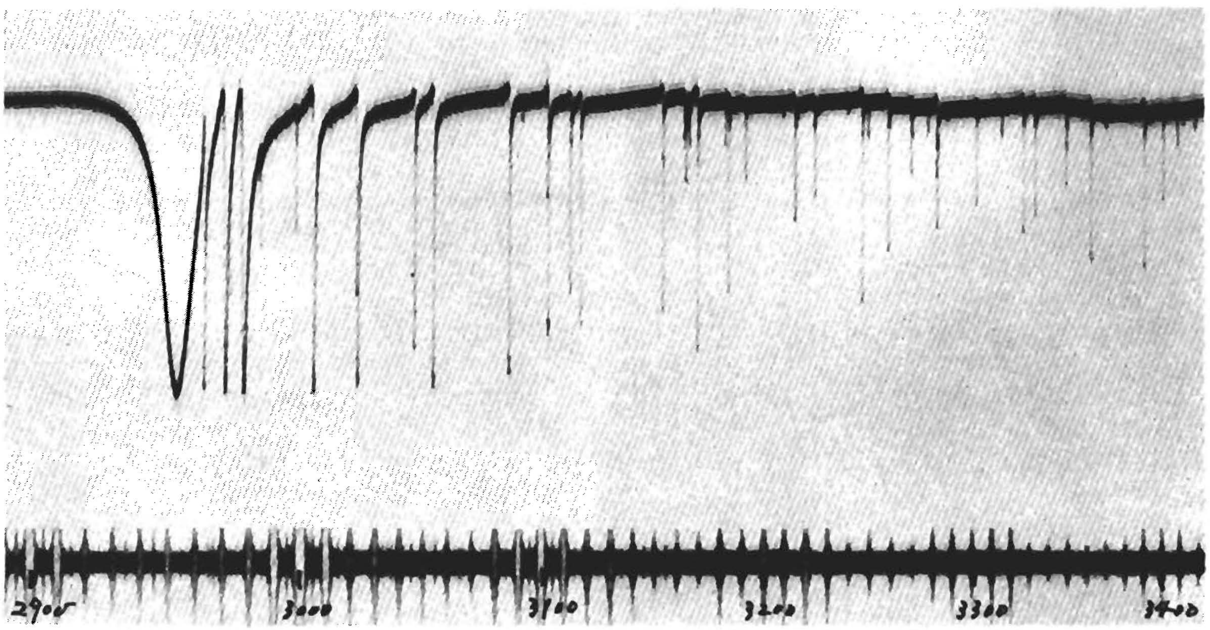
Figure 46 (Continued). Spectra of Beveled Quartz Crystal with Electrode 15 Mm in Diameter.

was connected to the upper main electrode. The similarity of the shapes of the records (b) and (c) (except where the shorts occur at the edge of the main upper electrode in (b)) indicates that the point of connection of the back-up electrode is immaterial. The records of Figure 48 were made with a new crystal, SCB-5, which does not display the asymmetry of crystal SCB-2 discussed below. Similar curves with crystal SCB-2 were not suitable for reproduction.

The shape and dimensions of the beveled crystal are indicated in Figure 49(a). Figure 49(b) shows superimposed polarization records for crystal SCB-2 with full electrode (28 mm) and with the 9.5-mm electrode. The responses are normalized to the same peak amplitude. The asymmetry is believed to

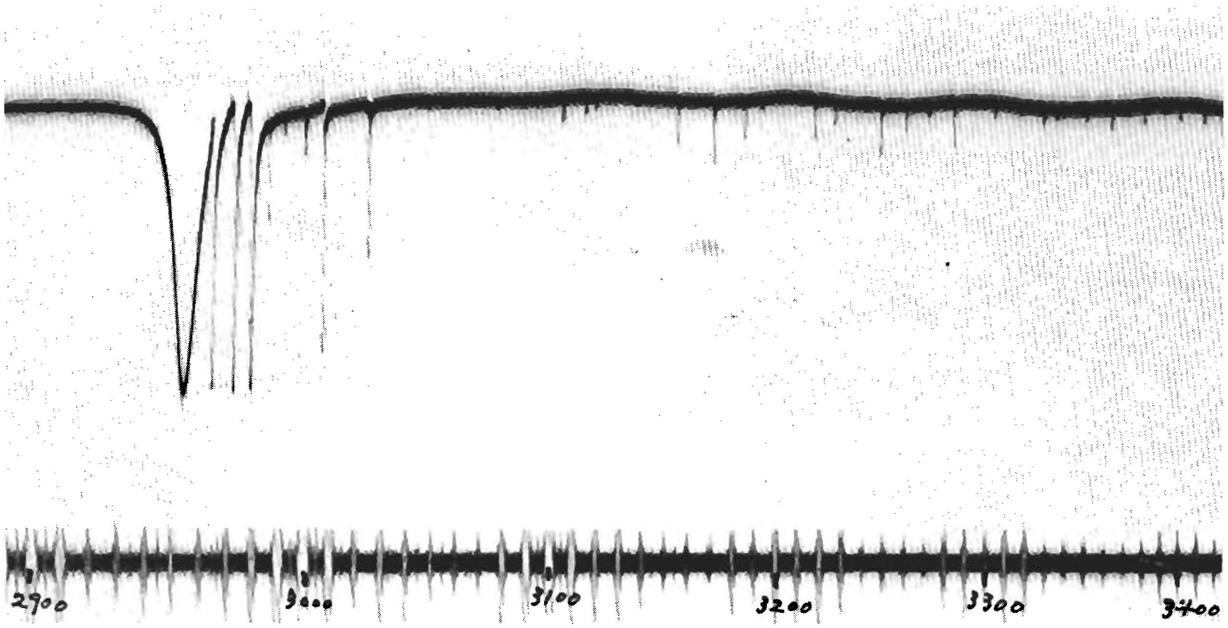


(a) UPPER ELECTRODE OF 28 mm DIAMETER.

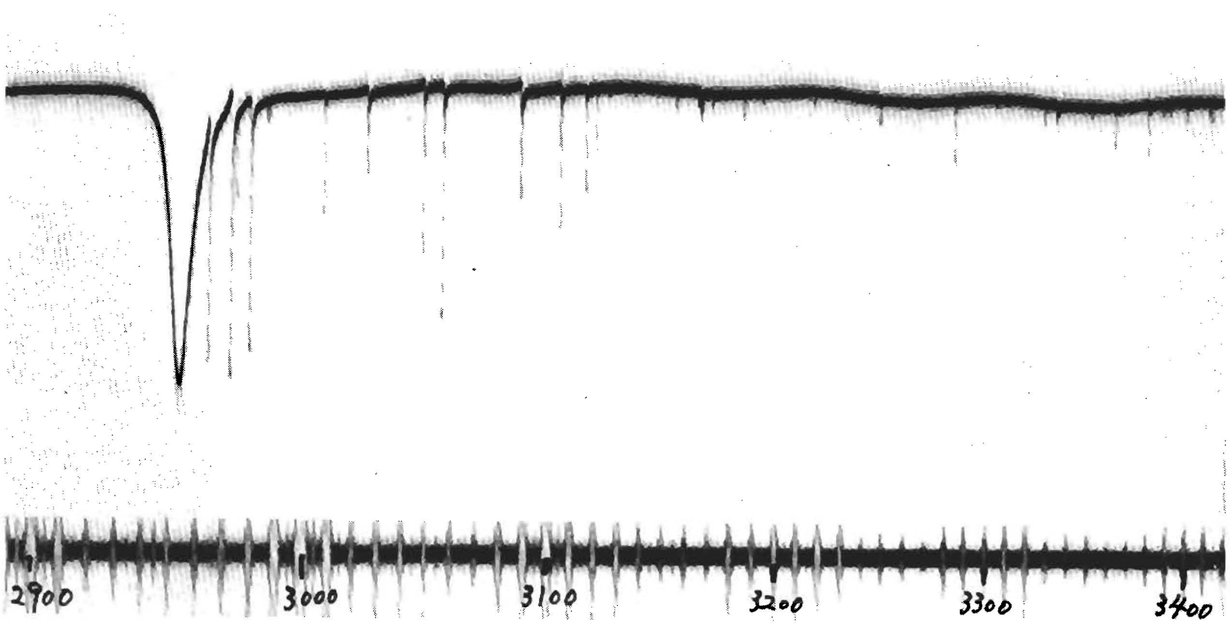


(b) UPPER ELECTRODE OF 24 mm DIAMETER.

Figure 47. Spectra of a Beveled Circular Quartz Crystal 28 Mm in Diameter Near the Fundamental Frequency (3 Mc/Sec).

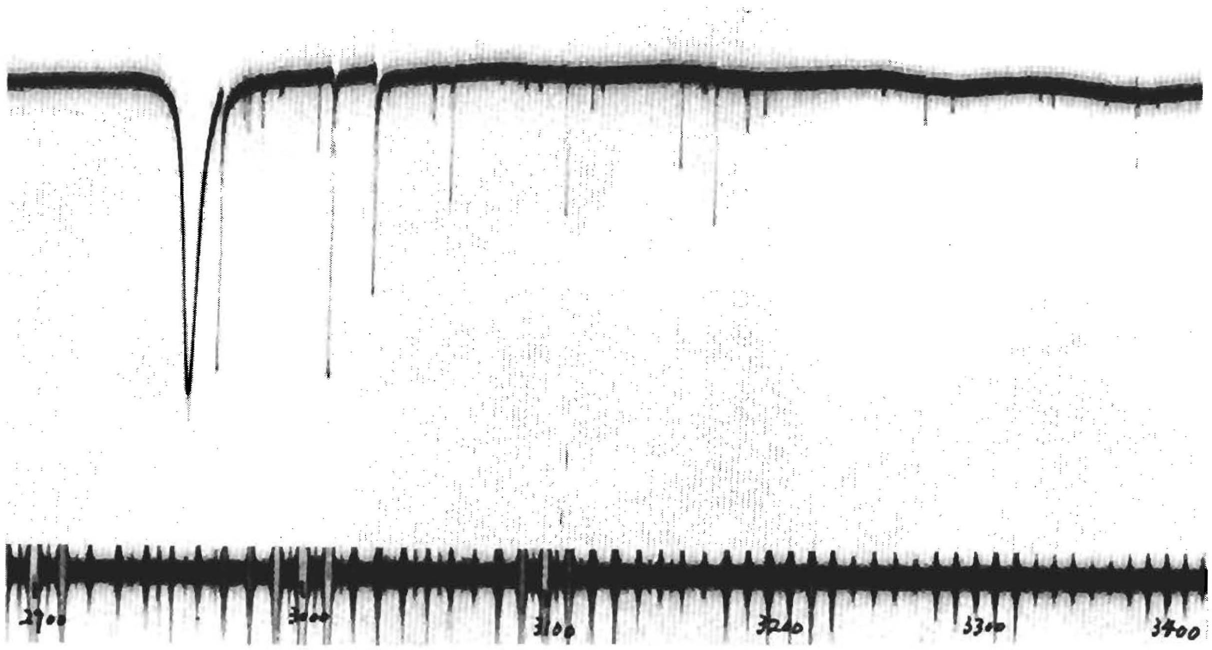


(c) UPPER ELECTRODE OF 21 mm DIAMETER.

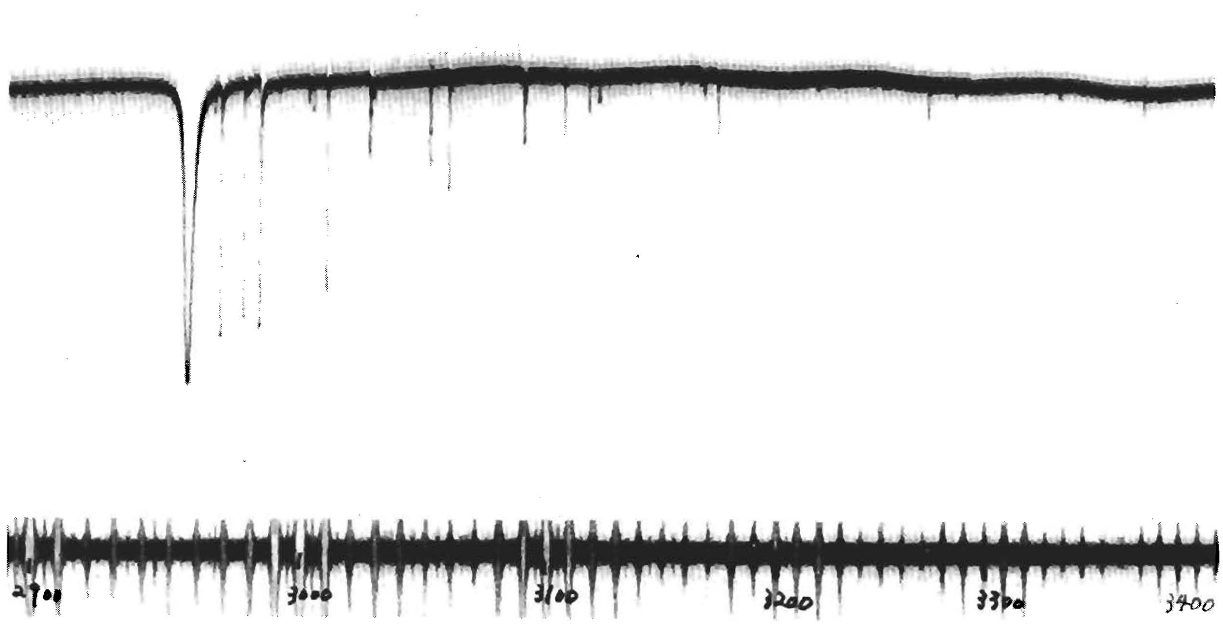


(d) UPPER ELECTRODE OF 18 mm DIAMETER.

Figure 47 (Continued). Spectra of a Beveled Circular Quartz 28 Mm in Diameter Near the Fundamental Frequency (3 Mc/Sec).

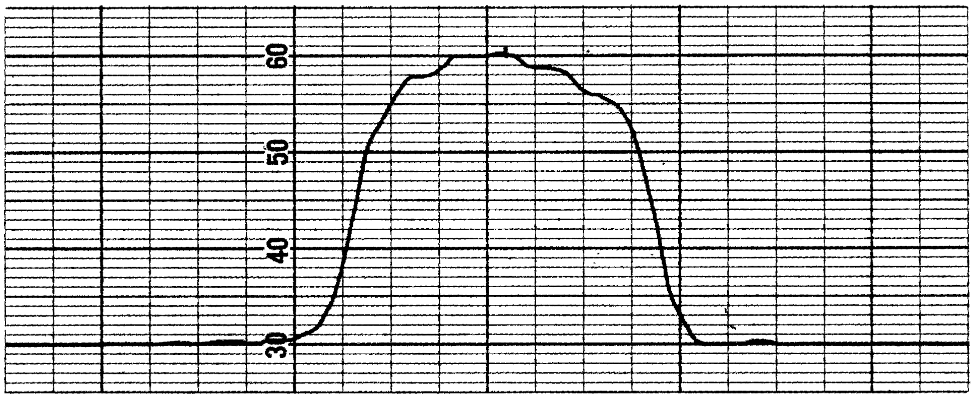


(e) UPPER ELECTRODE OF 15 mm DIAMETER.

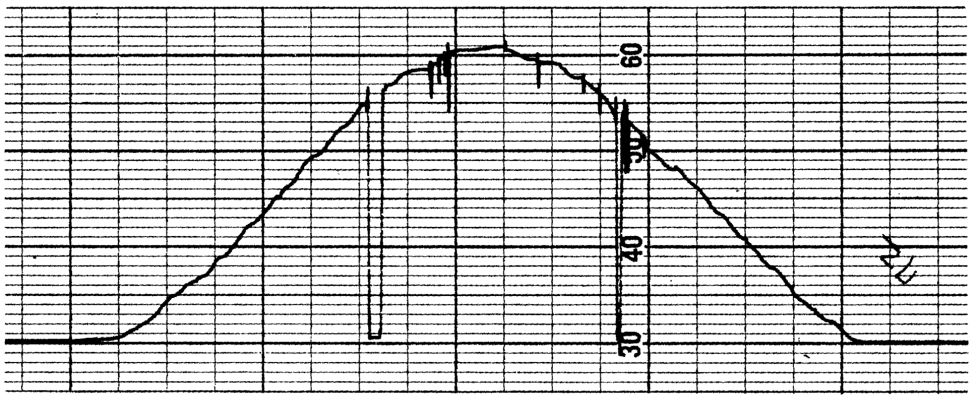


(f) UPPER ELECTRODE OF 12 mm DIAMETER.

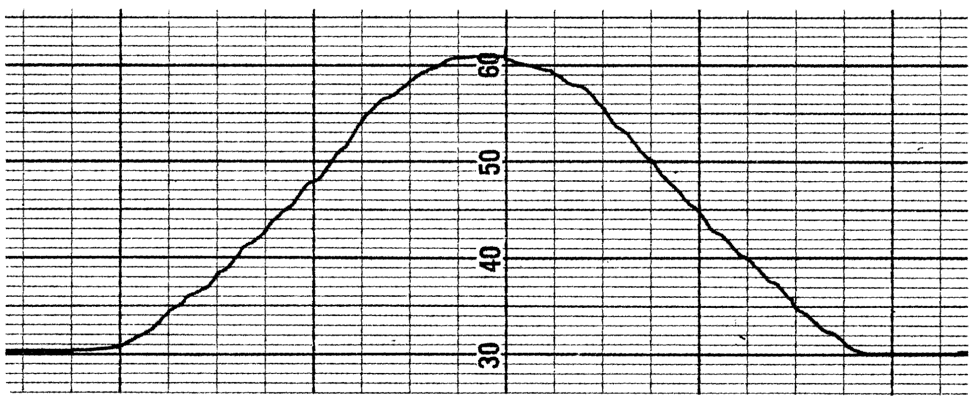
Figure 47 (Continued). Spectra of a Beveled Circular Quartz 28 Mm in Diameter Near the Fundamental Frequency (3 Mc/Sec).



(a) WITHOUT BACK-UP ELECTRODE



(b) GROUNDED BACK-UP ELECTRODE



(c) BACK-UP ELECTRODE CONNECTED TO MAIN ELECTRODE

Figure 48. Effects of the Back-up Electrode on the Polarization Traces.

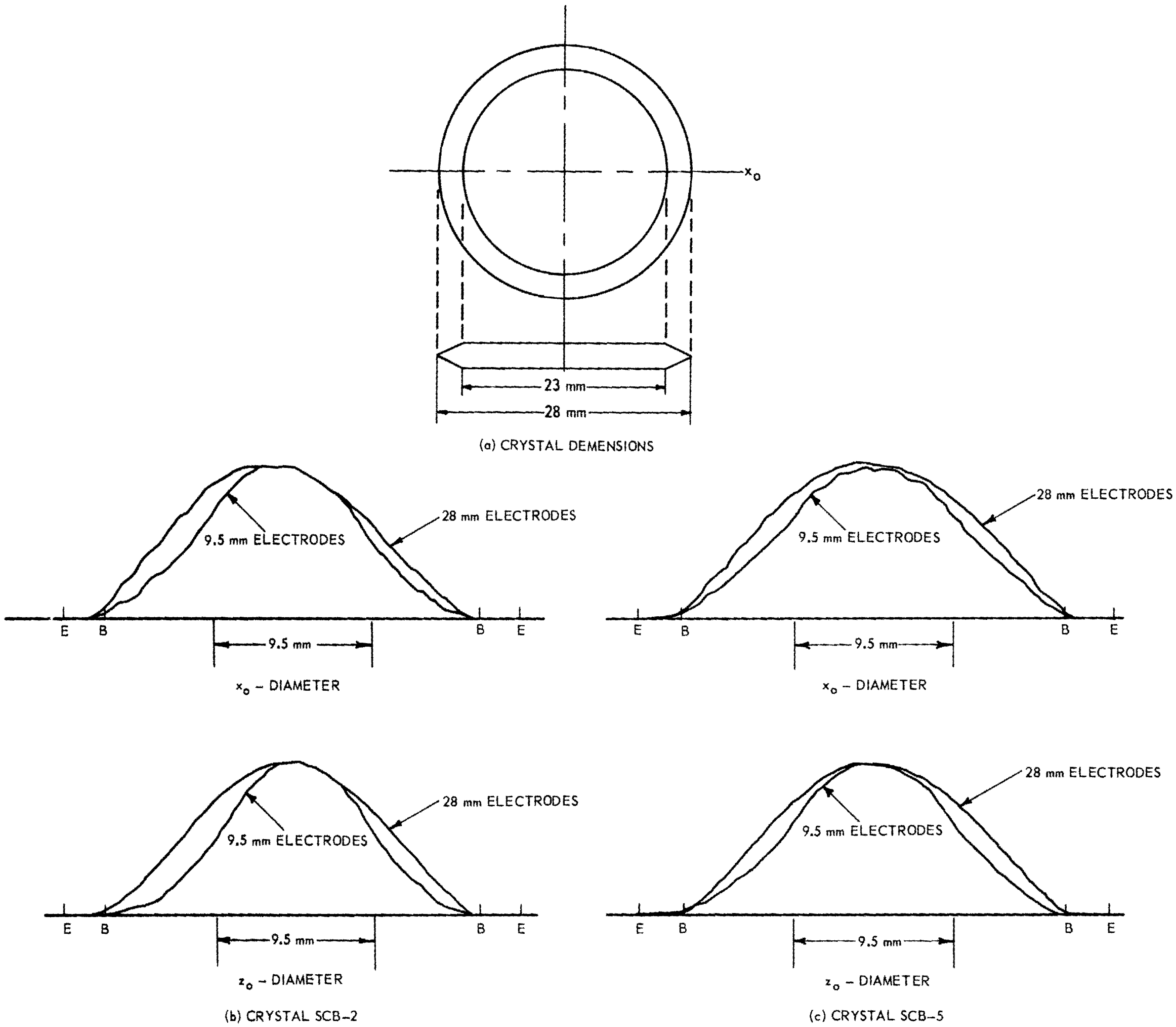


Figure 49. Probe Records.

result from a lack of perfection of the crystal. Records of a second crystal of the original four showed an even greater asymmetry. Near the end of the contract period, a new crystal, SCB-5, with highly polished surfaces parallel to within 1/10 wavelength of light was procured. The improvement in symmetry and centering of the trace for the 9.5-mm electrode is evident in Figure 49(c).

e. Motional Capacitance. The motional capacitance of crystal SCB-2 was measured with a crystal impedance meter for a number of electrode sizes. The measurements were made with a full size electrode on one side of the crystal and a copper plate of the desired size resting on the other. The ratio of the motional capacitance measured with each electrode to the capacitance of the full electrodes is shown in Figure 50.

The possibility of deriving the ratio of the motional capacitance of the crystal with electrodes of reduced size from the measured polarization traces of crystal SCB-2 was examined. It is evident that the relation between the polarization measures and the motional capacitance is not straightforward.

The measurements of crystal SCB-2 are unsuited for careful analysis because of imperfection of the surfaces. It is now evident that a crystal of the quality of finish of SCB-5 will give symmetrical polarization traces, desirable for careful analysis.

Further work at Georgia Tech in this interesting area must be deferred.

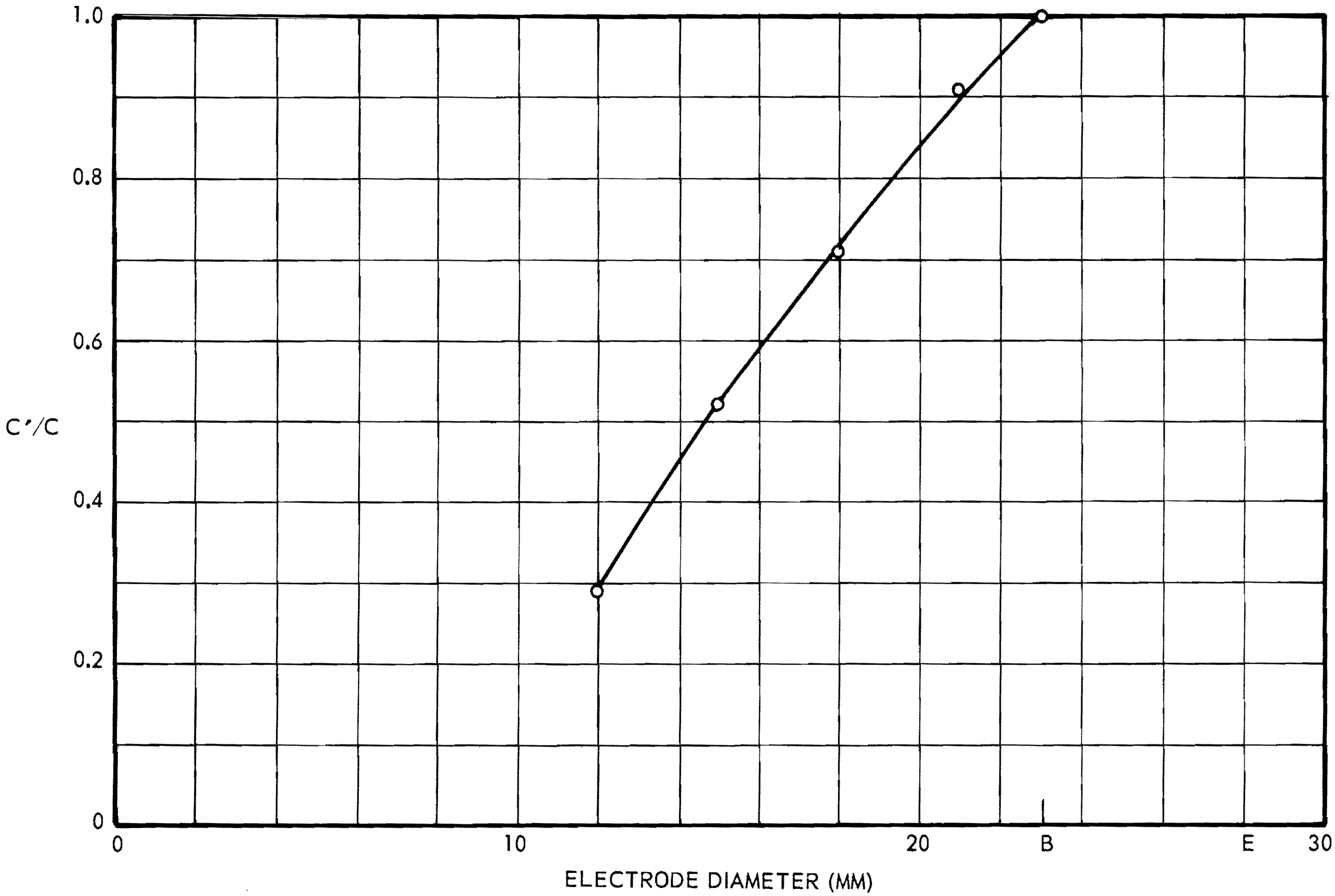


Figure 50. Ratio of Motional Capacitance Measured with Small Electrode to that with Full Electrode.

B. Phase II. Equivalent Electrical Parameters

1. Introduction

This phase of the work, assigned the Project No. A-402-12 by the Engineering Experiment Station of the Georgia Institute of Technology, was initiated on 1 March 1959 and was a continuation of the work prior to that date on Contract No. DA-36-039 SC-78910, Project No. A-402-2.

Project A-402-12 was essentially a continuation of the work which was begun and continued under Contracts DA-36-039 SC-56730, DA-36-039 SC-71191, DA-36-039 SC-74948, and DA-36-039 SC-78910 with special emphasis on the design and construction of a prototype Crystal Impedance Meter type of instrument for use in the frequency range from 150 to 300 mc/sec.

Under Contract DA-36-039 SC-74948, the construction of a useable Crystal Measurements Standard capable of measuring the two-terminal parameters of quartz crystals from 150 to beyond 300 mc/sec was essentially completed. Some slight improvements in the system were made under Contract DA-36-039 SC-78910. Under these contracts, various analyses of typical quartz crystal parameters were made. These analyses resulted in the establishment of a set of typical parameters of quartz crystals in the frequency range up to 500 mc/sec.

Some investigations of crystal oscillator circuits for use at frequencies above 200 mc/sec were conducted under Contract DA-36-039 SC-78910.

The circuits were primarily of the capacitance-bridge configuration.

From the analyses of the Crystal Measurements Standard data and from the experiments with crystal-controlled oscillators, a list of the more important parameters of high-frequency crystals was proposed. This list includes all of the basic quantities which a Crystal Impedance Meter type of instrument should be capable of measuring. A substitution measurement system for determining these parameters was described in the Interim Report of the current contract. The system consists of a component mount into which the crystal or substitution resistor is plugged, a signal source, and a suitable voltmeter. Two models of the component mount were previously described. Data were presented to compare the measurements from the substitution system with those from the Crystal Measurements Standard System.

In Report No. 2 (Quarterly) of the current contract, a comparison between substitution measurements and Crystal Measurements Standard measurements showed a maximum disagreement of less than 4 percent for resistance and less than 0.0002 percent for frequency. The procedure for determining an equivalent crystal Q was also discussed.

A frequency stabilization system for the Marconi Signal Generator was also described in Report No. 2 (Quarterly). At that time, a complete breadboard model of the system had been constructed and tested. Both long- and short-term frequency variations of the Signal Generator were greatly reduced by the system.

In Report No. 3 (Quarterly), the measurement of equivalent crystal Q was reported. The measurements generally disagreed by less than 10 percent with values calculated from Crystal Measurements Standard data for crystals having reasonably high Q's. The detailed step-by-step procedure for making the substitution measurements was also described in Report No. 3 (Quarterly). Further work with the substitution measurement system was discontinued at the end of the third report period.

During the fourth and fifth report periods, efforts were devoted almost entirely to the construction and testing of high-frequency crystal-controlled oscillators. Several vacuum-tube oscillators were described in Report No. 4 (Quarterly). During the fifth report period, crystal temperature coefficient data were obtained. Also, several transistorized crystal-controlled oscillators were constructed. These more recent data are presented only in this Final Report.

Most of the data and discussions from all five report periods are in-included in this Final Report so that references to previous reports of this contract are generally unnecessary. One of the exceptions is the servo frequency control system for the Marconi Signal Generator which was discussed in Report No. 2 (Quarterly). This system was never fully completed because of the change in emphasis to oscillator construction and testing and, thus, is not included in this Final Report.

(2) antiresonating element value, (3) frequency at antiresonance, (4) conductance at antiresonance, and (5) minimum conductance at frequencies away from antiresonance.

Several novel methods for measuring crystal parameters at high frequencies have been considered. One of these, referred to as the Equivalent Circuit Crystal Measurement Method, was investigated under Contract No. DA-36-039 SC-74948. This method was intended primarily for measuring the motional-arm parameters of quartz crystals and thus did not meet the requirements outlined above. A second measurement system, which was called the Substitution Measurement System, has been investigated during the current contract.

The equivalent circuit of the Substitution Measurement System is shown in Figure 51. The crystal is antiresonated by a shorted stub and placed across an r-f signal source having an internal impedance of 50 ohms. For a constant source voltage, the voltage appearing across the crystal may vary from zero to the source voltage as the crystal impedance is varied from zero to infinity. For the finite variations in crystal impedance, such as occur near crystal resonances, the expected variations in crystal voltage are shown in the lower part of Figure 51. This voltage as a function of frequency is measured by means of a diode detector and d-c voltmeter or d-c oscilloscope.

For the circuit shown, the voltage across the crystal, E_c, is given by

$$E_c = \frac{E}{1 + 50Y} = \frac{E}{50} \left(\frac{1}{0.02 + Y} \right) ,$$

where E is a constant source voltage and Y is the crystal admittance. Since E is a constant, $|E_c|$ is a maximum when $|1 + 50Y|$ is a minimum.

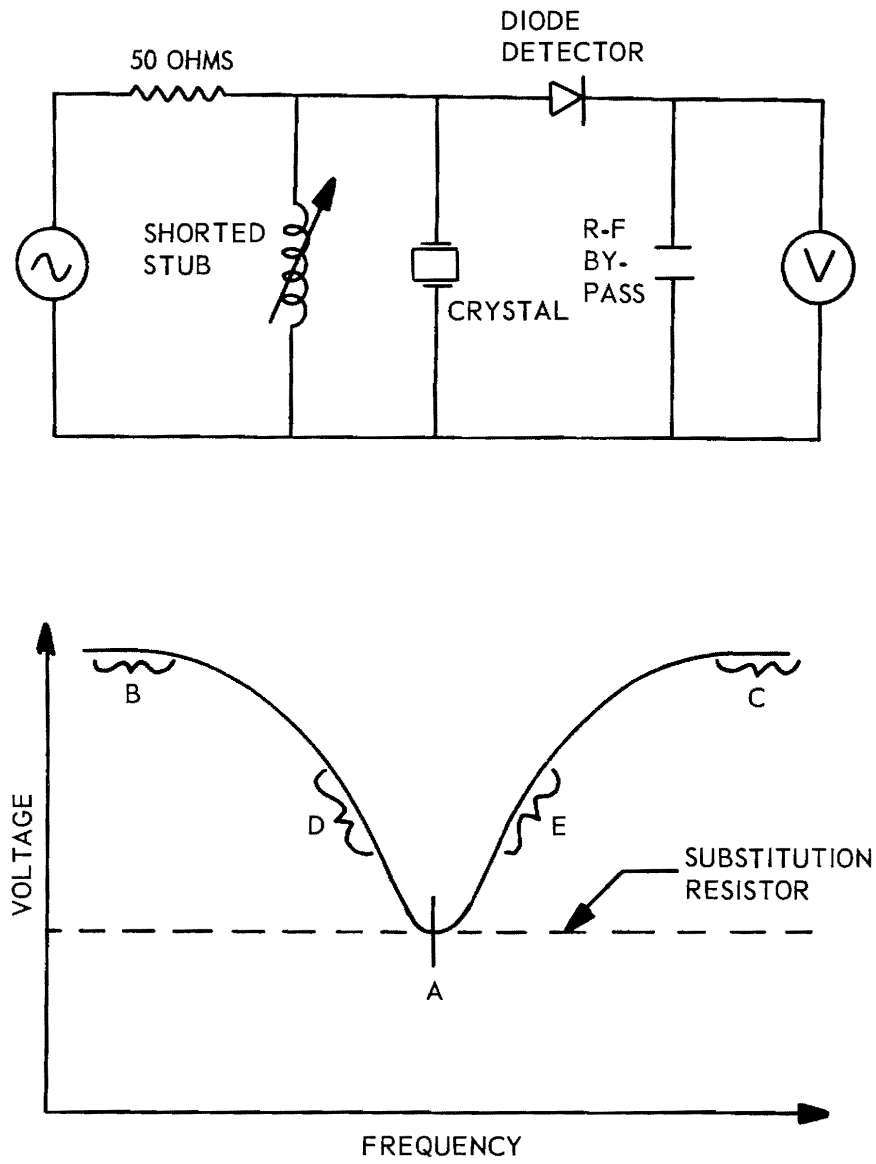


Figure 51. Equivalent Circuit of the Substitution Measurement System.

The admittance, Y, of a crystal at an overtone response is approximated by a circle in the right half of the complex plane, generally the upper quadrant, as shown in Figure 52, position 1. The length of a vector (Y + 0.02) from the point (-0.02, 0) to any point on the circle varies with frequency with the minimum and maximum values determined by the diameter and position of the response circle. Both the minimum and maximum values occur when the vector (or its extension) passes through the center of the circle. The vector $Y_A + 0.02 = Y'_A$, of Figure 52 represents the maximum value of (Y + 0.02) as the frequency is varied. Since E_c is inversely proportional to (Y + 0.02), point A of Figure 51 indicates the frequency of the vector Y'_A.

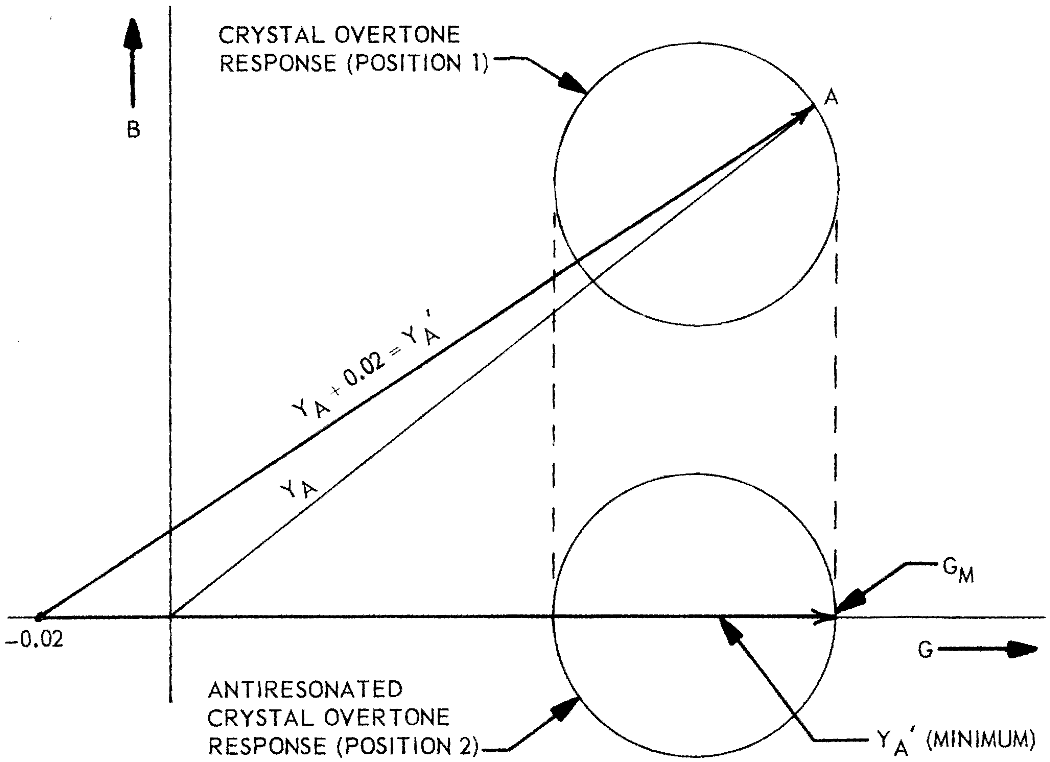


Figure 52. Admittance Vectors of the Substitution Measurement System.

If the crystal is paralleled by a shorted stub, the response circle may be moved up or down but remains the same diameter as long as the range of frequencies considered remains insignificant compared to the absolute frequency of the response. As the length of the stub is changed, the length of Y_A' and height of point A of Figure 51 will both change. In Figure 52, G_M represents the maximum conductance of the crystal response and occurs at the same frequency regardless of the stub setting. However, as the setting of the stub is changed so that the response circle is moved from position 1 to position 2, the length of Y_A' and the frequency at which it occurs and thus the height and position of point A of Figure 51 are all changed. The minimum length of Y_A' occurs when the response is in position 2. Also, in this position, Y_A' is purely conductive and $(Y_A' - 0.02)$ is equal to G_M. This condition is indicated by adjusting the shorted stub for a maximum height of point A of Figure 51. This maximum conductance may be calculated if the voltage across the crystal at point A and the source voltage are both known and if the source impedance is purely resistive and is accurately known.

Alternately, if the crystal is replaced by a substitution resistor having a conductance equal to G_M, and any susceptive component of the resistor is canceled by the stub, the voltage will be constant with respect to frequency as indicated by the dashed line through point A of Figure 51. The susceptive cancellation is accomplished by adjusting the stub for a maximum height of the dashed line. A different value of conductance will also produce a straight line but it will not pass through point A.

Successive substitutions may be made until a resistor is found which produces the same output voltage as does the crystal. The substitution procedure for determining G_M is more direct and less time consuming than is the procedure requiring an accurate knowledge of the source impedance.

The crystal antiresonant frequency is readily determined since it can be read directly at point A of Figures 51 and 52. The element required to antiresonate the crystal can be read or calculated directly from the shorted stub. In a similar manner, the minimum conductance of the crystal can be determined in regions B or C of Figure 51.

The equivalent Q of the crystal can be determined from measurements in regions D and E by making both frequency and impedance magnitude measurements. A principal difficulty in measuring Q is, however, encountered in defining the quantity for a circuit which cannot be represented by a simple series resonant circuit. The Q can be defined in terms of stored and dissipated energies; however, a more appropriate definition of Q for a crystal appears in terms of the phase angle as a function of frequency. The quantity, $d\theta/df$, at a point of zero susceptance, is indicative of expected oscillator stability and will be accepted as the basis for the definition of Q. Thus, for a high-frequency quartz crystal, Q will be defined as:

$$Q = \frac{f_o}{2} \cdot \left.\frac{d\theta}{df}\right|_{\text{susceptance} = 0},$$

where θ is the phase angle of the crystal admittance.

For measurement purposes, $d\theta/df$ must be approximated by $\Delta\theta/\Delta f$. If Δf is kept small, little error is introduced. To determine the error magnitude for a typical crystal, a theoretical typical crystal characteristic was plotted on a rectangular coordinate as shown in Figure 53. The actual Q was calculated from the slope of a curve of phase angle versus frequency (not shown). The values of Q for various combinations of data points are indicated by the connecting lines in the figure.

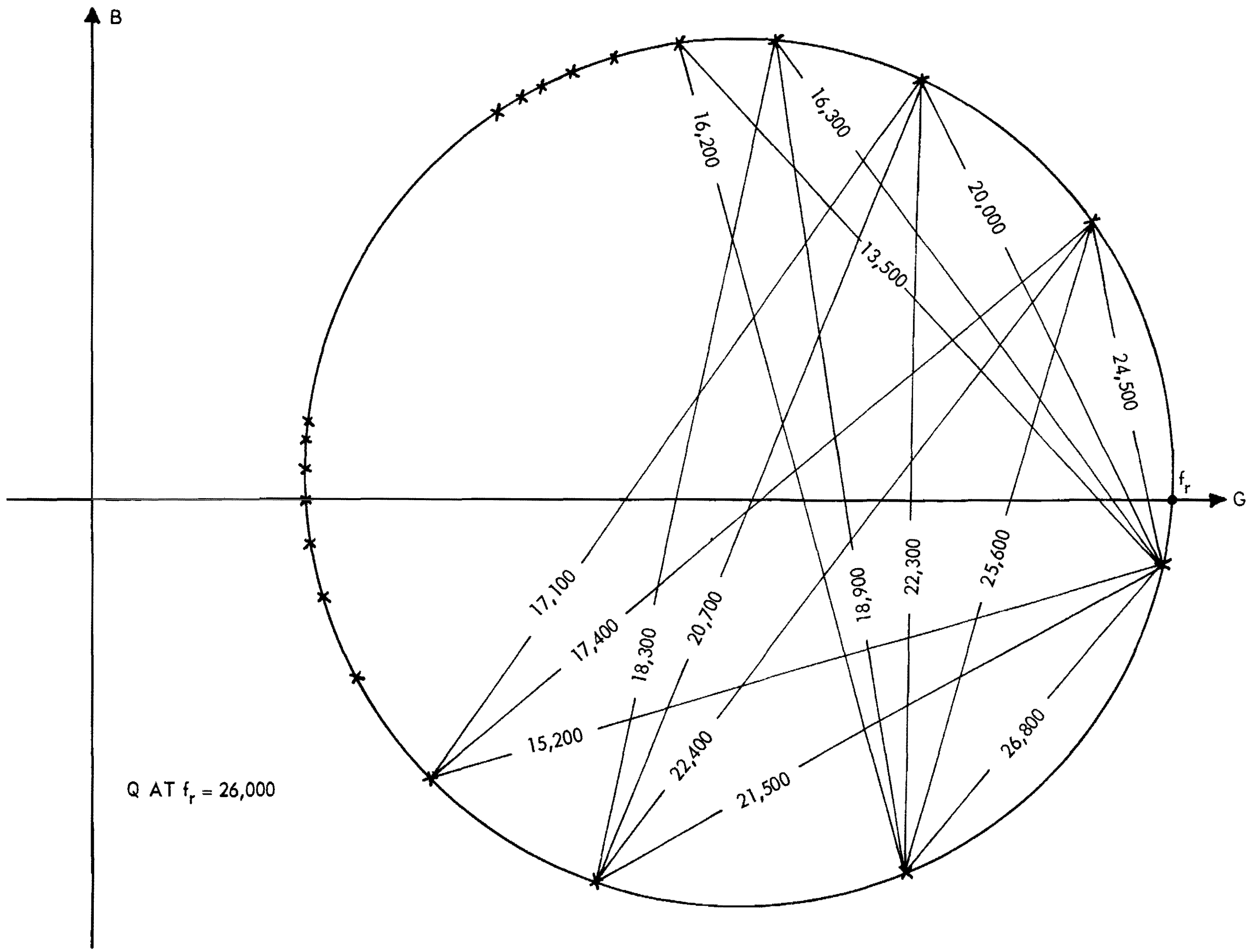


Figure 53. Q Approximations for a Theoretical Crystal at 300 Mc/Sec.

For the determination of the Q of a crystal, G_{max} and G_{min} are first determined as described in a later section. If a substitution resistor with a conductance G_k, less than G_{max} and greater than G_{min}, is placed in the component mount and the shorted stub is adjusted as for conductance determinations, curve C of Figure 54 is obtained for the sweep mode of operation. This curve is observed to be a straight line. If the position of the line is marked on the display and if the resistor is replaced by the crystal, curve D is obtained after proper adjustment of the shorted stub. Points A and B represent the intersections of the two curves. The frequencies at points A and B may be determined by reducing the sweep to zero deviation at these points.

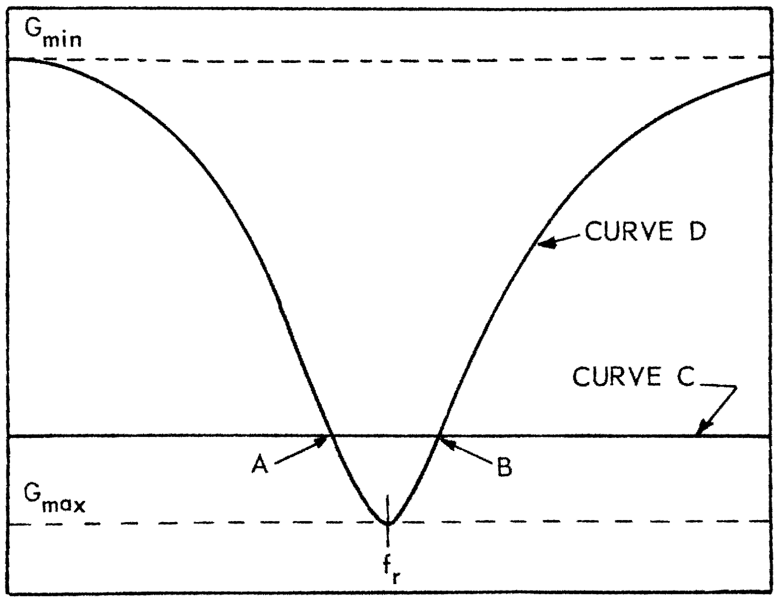


Figure 54. Sweep Display with the Substitution Measurement System.

Figure 55 shows the admittance function of the antiresonated crystal plotted on rectangular coordinates. Points A and B correspond to the curve

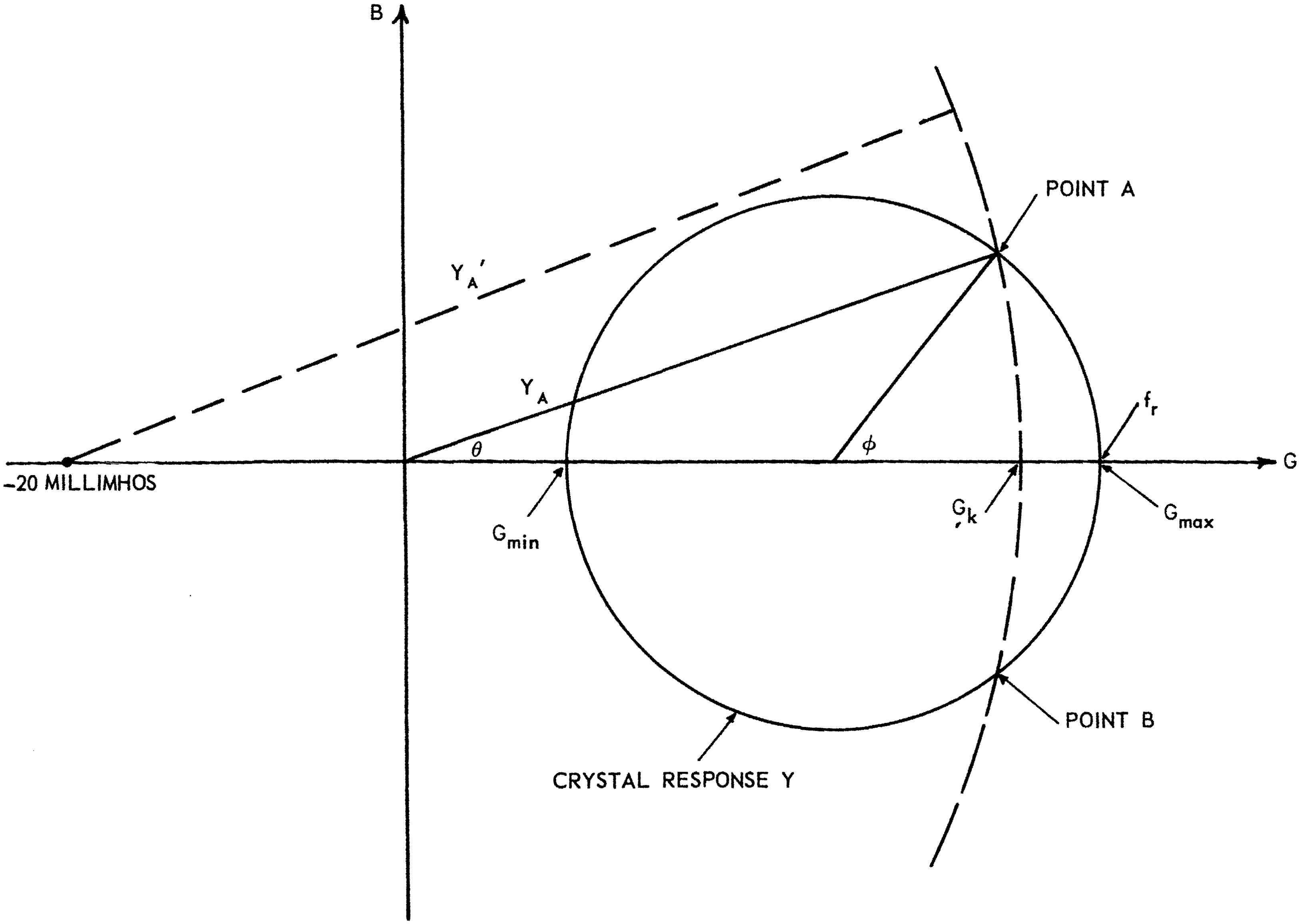


Figure 55. Admittance Vector Diagram for the Substitution Measurement System.

intersections of Figure 54. The approximate Q of the crystal can be determined by calculating θ of Figure 55 since the frequencies at points A and B are already known. The angle, θ, however, is a function of three quantities, G_{max}, G_{min}, and G_k. For any given value of G_k, a family of curves can be constructed from which θ, as a function of G_{max} and G_{min}, can be determined. Since approximately 25 values of substitution resistors are presently available, 25 families of curves would be required to determine Q for a random selection of G_k.

An alternate procedure for determining θ would be to select G_k as some specified function of G_{max} and G_{min} so that only one family of curves would be required. The equation for θ, which may be derived from Figure 55, is

$$\theta = \mathrm{Cos}^{-1} \frac{G_k^{\,2} + 40\, G_k + G_{max}\, G_{min}}{\sqrt{G_{max} + G_{min} + 40}\;\sqrt{(G_{max} + G_{min})(G_k^{\,2} + 40\, G_k + G_{max}\, G_{min}) - 40 G_{max}\, G_{min}}}.$$

For good accuracy in determining θ, the angle Φ of Figure 55 should be between 30 and 90 degrees. Theoretical studies have shown that, for typical crystals, Φ will be restricted to angles between 45 and 55 degrees if $G_k = 0.85\, G_{max} + 0.15\, G_{min}$. Also, the equation for θ may now be expressed in terms of two variables, G_{max} and G_{min}, and only one family of curves is required. This family of curves is shown in Figure 56. A quality factor, Q', may now be defined as;

$$Q' = \frac{f_o}{2} \cdot \frac{\Delta\theta}{\Delta f}$$

where $\Delta\theta$ is two times the value of θ as determined from the curves of Figure 56 and Δf is $(f_B - f_A)$. The quantity Q' will differ from the defined Q by a relatively constant percentage since the angle Φ remains nearly constant under the chosen condition for G_k.

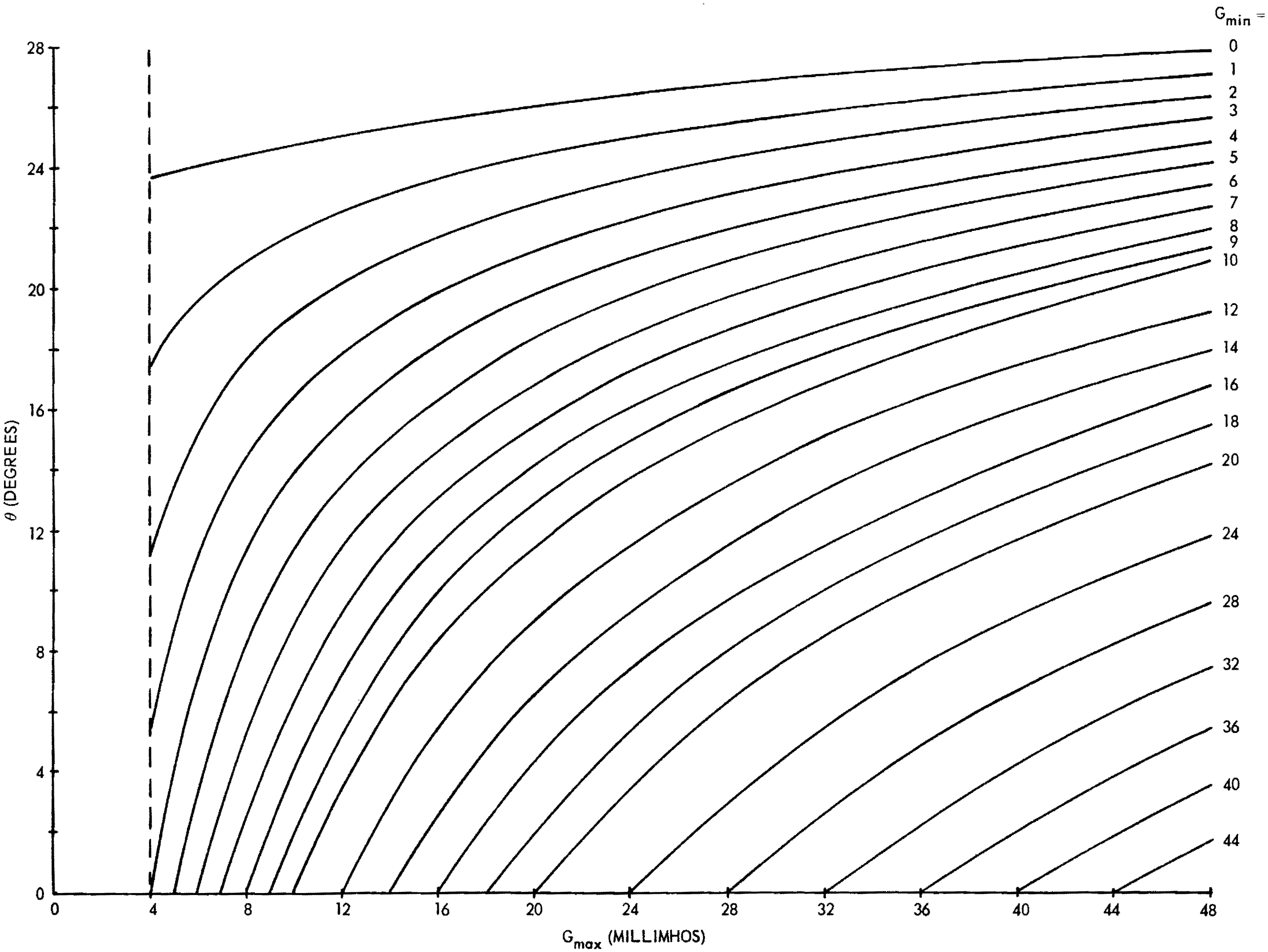


Figure 56. θ- Curves for $G_k = 0.85\ G_{max} + 0.15\ G_{min}$.

If the overtone response of a crystal is not a perfect circle with symmetrical frequency distribution, additional errors in Q determination will be introduced. Spurious responses close to the main response can readily produce such errors.

The detailed steps in making a crystal measurement will be discussed later after the actual equipment has been described.

b. Construction and Calibration of Substitution Resistors. An essential part of the Substitution Measurements System is a set of substitution resistors which have been accurately calibrated. In the initial laboratory tests a set of resistors from a Crystal Impedance Meter Type TS-683/TSM was used. Since these resistors did not adequately cover the desired range in sufficiently small increments, additional resistors were constructed on standard HC-6 crystal bases with standard-tolerance Allen-Bradley 1/2-watt composition resistors. The resistor elements were filed to obtain the required resistance values.

The laboratory-constructed resistors were mechanically protected by tap-soldering HC-6 metal cans to the bases rather than hermetically sealing the units since the resistance values were found to be permanently affected by high temperatures.

The complete set of resistors was calibrated with the Crystal Measurements Standard System. Figure 57 shows the conductive components of the admittances as functions of frequency. The susceptive compenents, which were less than 15 millimhos for all but two of the resistors from 175 to 300 mc/sec, were of no concern since these components are canceled by the shorted stub of the Substitution Measurements System. Figure 57 includes corrections for line lengths and predetermined Admittance Meter errors. The necessary calculations

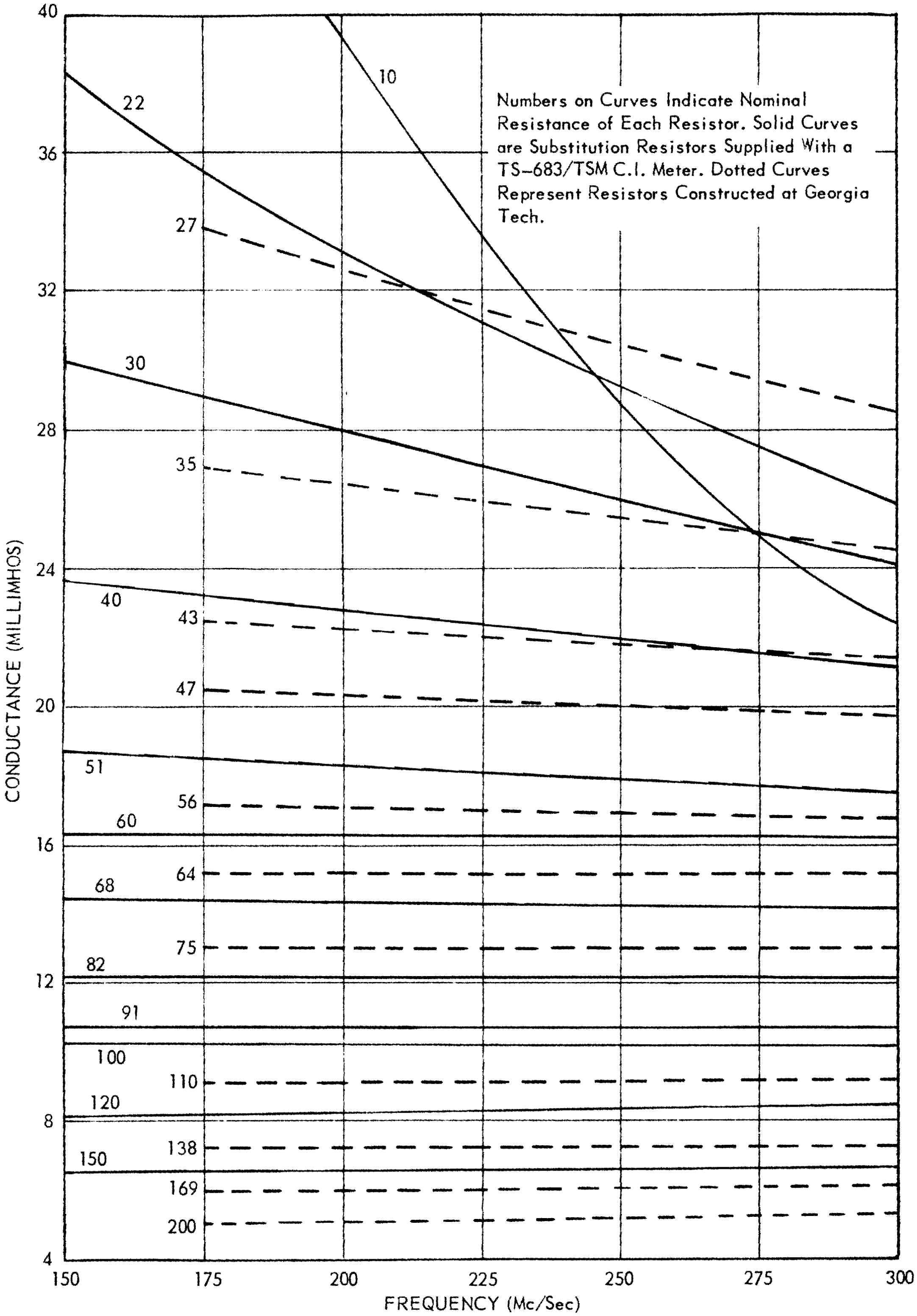


Figure 57. Calibration Curves for Substitution Resistors.

were performed by the usual digital computer programs.

c. The initial Substitution Measurement System. Figure 58 is a drawing indicating the construction of the first model of this measurement equipment. A General Radio Type 874-EL adapter was modified for use as the crystal mount. The constant source impedance was provided by a Marconi Signal Generator followed by two IFI chain amplifiers and appropriate 50-ohm attenuators. A photograph of the mount with a crystal in test position in shown in Figure 59.

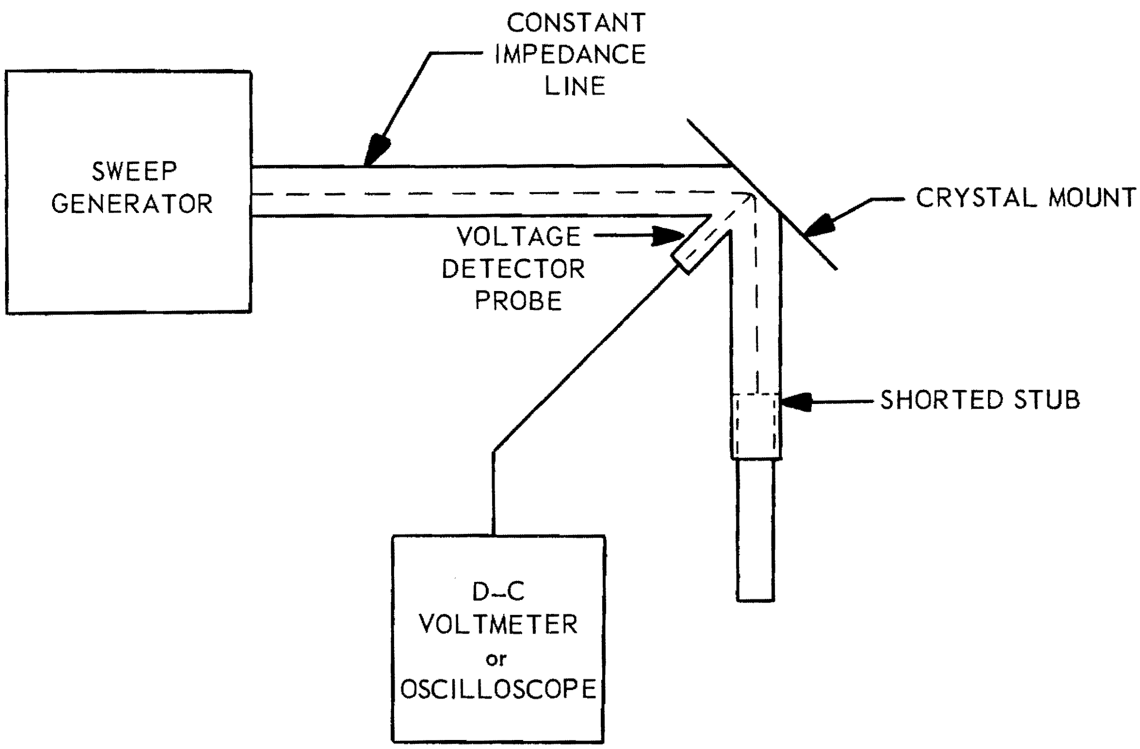


Figure 58. Block Diagram of the Substitution Measurement System.

Although actual measurements are generally made at fixed frequencies, the overtone responses may be more readily found by using a sweep frequency

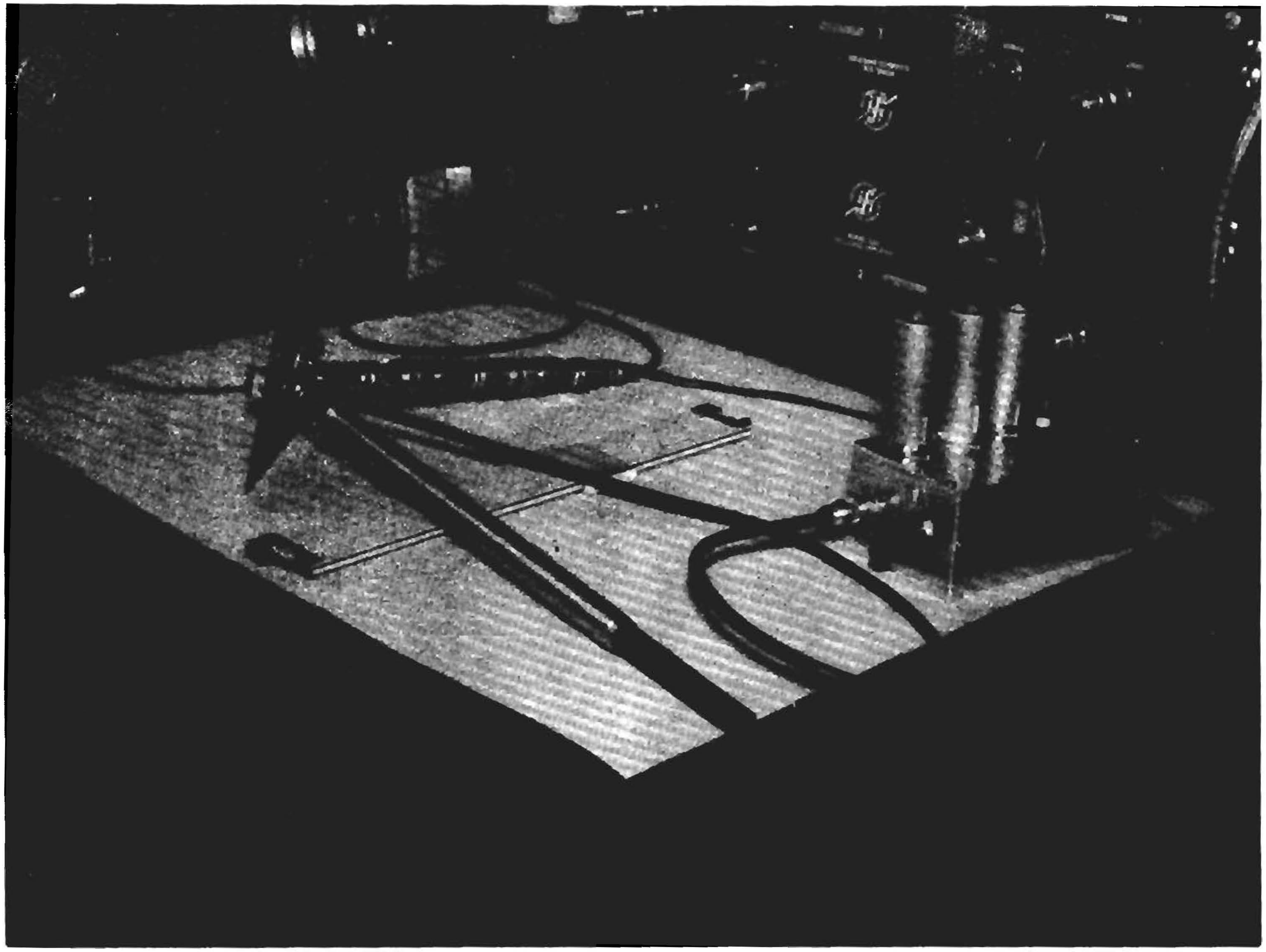
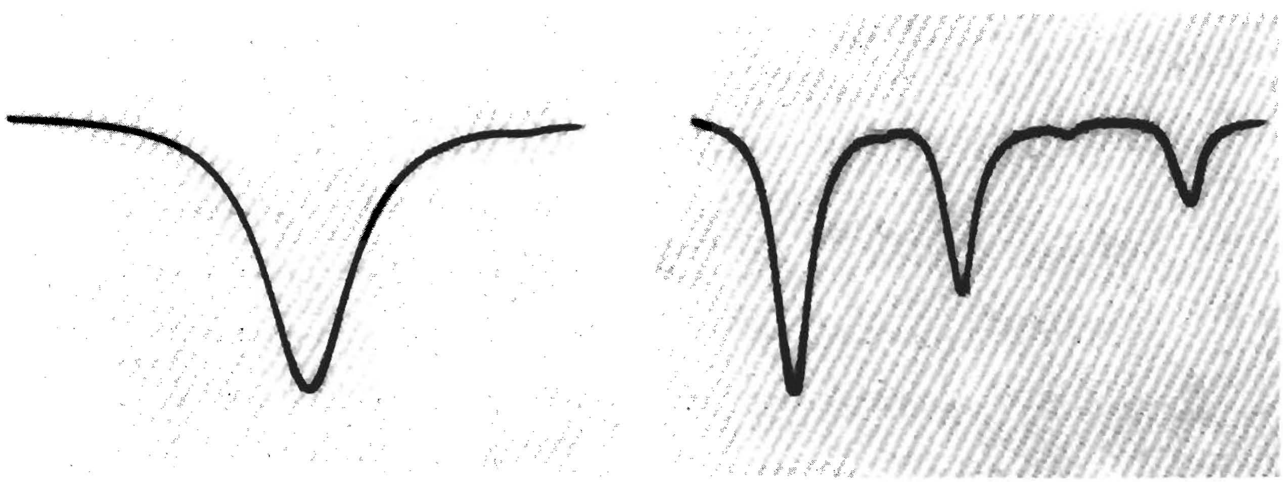


Figure 59. Prototype Substitution Measurement System.

generator with a synchronized oscilloscope for visual indication. A motor-driven sweep potentiometer, as may be seen in the background of Figure 59, was originally used to provide a slow sweep of about 10 kc/sec^2. The original intention was to use the sweep generator during an actual crystal measurement with a stable marker generator for frequency determination. Since such a marker generator was not available, the sweep mode of operation could not be used for frequency measurement. The motor-driven sweep potentiometer was replaced, therefore, by the sweep output voltage from a Tektronix oscilloscope. The more rapid sweep, 250 kc/sec^2, could produce frequency and resistance errors due to the high crystal Q if the sweep were continued during an actual measurement.

A direct-coupled amplifier, as shown at the right-center of Figure 59, was necessary to amplify the output of the diode detector sufficiently for presentation on the oscilloscope.

A typical crystal overtone response, as displayed on the oscilloscope, is shown in Figure 60.



A. MAIN RESPONSE

B. MAIN RESPONSE AND SPURIOUS RESPONSES

Figure 60. A Typical Overtone Response with the Substitution Measurement System.

The procedure for making a substitution crystal measurement is as follows:

Step 1. Set the equipment for sweep operation and locate the overtone response by tuning the Signal Generator frequency.

Step 2. Adjust the susceptance stub for a maximum value of point A of Figure 61 (point A is the minimum point on the curve regardless of the shape of the curve).

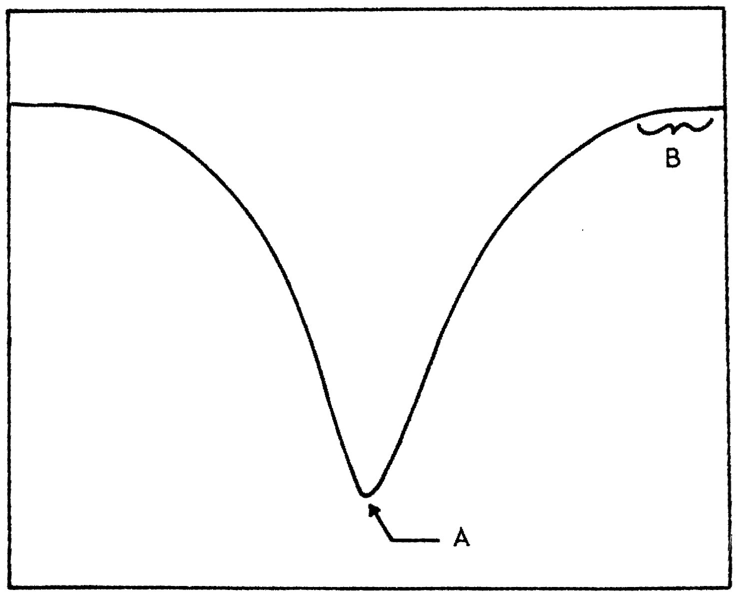


Figure 61. Ideal Sweep Characteristic with the Substitution Measurement System.

Step 3. Gradually reduce the sweep deviation while readjusting the frequency to maintain point A at the center of the sweep.

Step 4. When zero deviation is reached, observe the d-c microvoltmeter (which may be continuously connected across the mount diode along with the oscilloscope) and alternately adjust the frequency for a minimum voltage and the susceptance stub for a maximum voltage.

Step 5. Record the resulting voltage, frequency (f_r), and stub setting.

Step 6. Replace the crystal with a substitution resistor and adjust the stub for a maximum voltage.

Step 7. Repeat step 6 with other substitution resistors (employing linear interpolation, if necessary) until a maximum voltage equal to that observed in step 4 is obtained and record the calibrated resistance (or conductance) value as R_{min} (or G_{max}).

Step 8. Repeat the above seven steps using section B of Figure 9 and adjusting frequency in step 4 for a maximum rather than a minimum. (The only required permanent data point is given in step 7 as the resistance which is recorded as R_{max}, or the conductance, which is recorded as G_{min}.)

This eight-step procedure for determining the parameters of a crystal with the substitution measurement system yields: (1) the conductance at antiresonance, G_{max}; (2) the frequency at antiresonance or at G_{max}; (3) the minimum conductance away from antiresonance, G_{min}; and (4) the antiresonating element value in terms in stub length. The only remaining important parameter is the value of Q'. The necessary data for calculating Q' are obtained by continuing the measurement procedure as follows:

Step 9. Place a substitution resistor with conductance of $G_k = 0.85\, G_{max} + 0.15\, G_{min}$ in the mount, adjust the stub for minimum voltage, and record the voltage (if the exact substitution resistor is not available, linear interpolation may be used to determine this voltage).

Step 10. Reinsert the crystal and adjust the stub as outlined in step 4.

Step 11. Adjust the frequency to either side of the frequency of point A of Figure 61 until the voltage is the same as the voltage in step 9, repeat for the other side, and record the frequencies as f_1 (low side) and f_2 (high side).

Step 12. From Figure 56, determine θ and then calculate $Q' = \frac{f_r}{2}\left(\frac{2\theta}{f_2 - f_1}\right)$.

The procedure for determining the maximum crystal conductance and the corresponding frequency has been tested on several laboratory crystals between the frequencies of 150 and 300 mc/sec. A comparison of these data with the corresponding data from the Crystal Measurements Standard is presented in Table I The agreement is reasonably good except at the higher frequencies.

In an attempt to improve the high-frequency performance of the Substitution Measurements System, a second model of the crystal mount was constructed with a General Radio Voltage Rectifier Type 874-VR. Photographs of this mount are shown in Figure 62B with additional photographs of the first mount in Figure 62A. Table II is a summary of the measurements made with the second mount.

The Crystal Measurements Standard data of Table II were taken directly from a numerical tabulation of data collected 6 months previously. In many cases the errors in these data due to lack of frequency interpolation are greater than the disagreements with the Substitution Measurements System data. Where large differences were observed, the Crystal Measurements Standard data were rerun with a half-wavelength line between the Admittance Meter and the component mount. In some cases better agreement was obtained; in others no improvement was observed. Closer examination of data obtained with the various measurement systems has indicated that aging, drive-level variations, and temperature variations in most cases can account for even the largest discrepancies. For example, with one crystal unit at 250 mc/sec, a change in drive level from 0.01 to 1 mw changed the frequency by 0.0006 percent. The data from the Crystal Measurements Standard

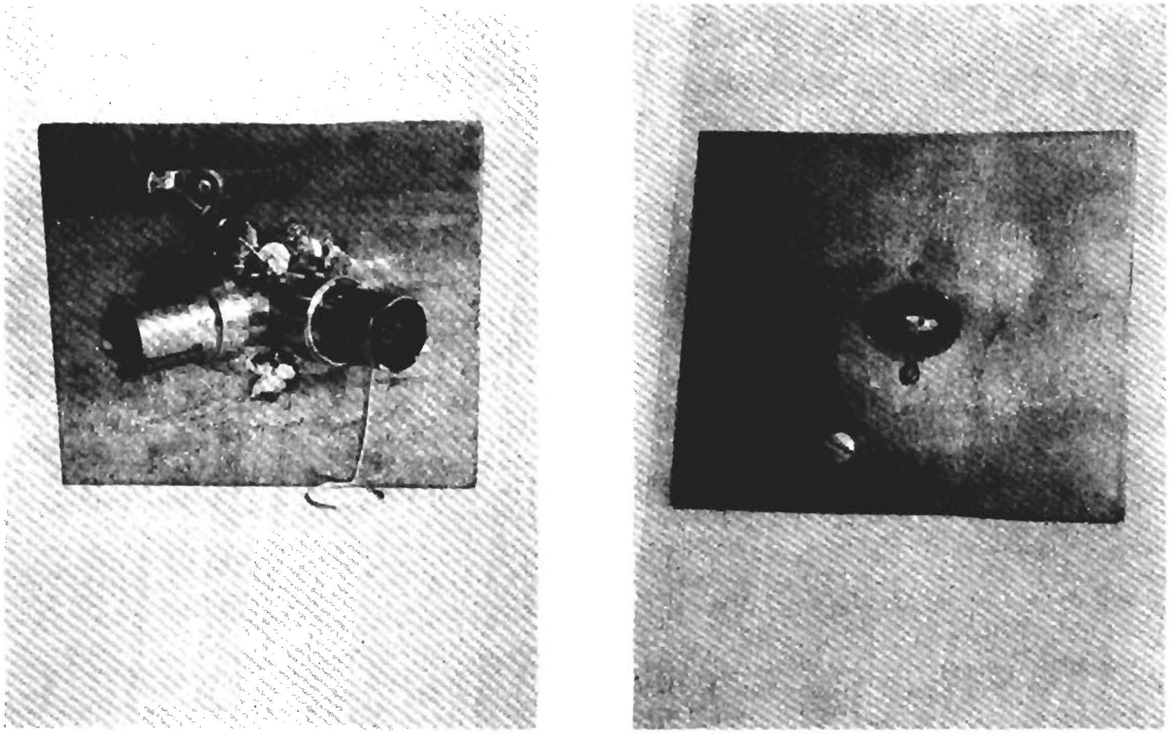
TABLE I

COMPARISON OF SUBSTITUTION MEASUREMENT-SYSTEM RESISTANCE MEASUREMENTS WITH CALCULATED MINIMUM RESISTANCES FROM THE CRYSTAL MEASUREMENTS STANDARD SYSTEM

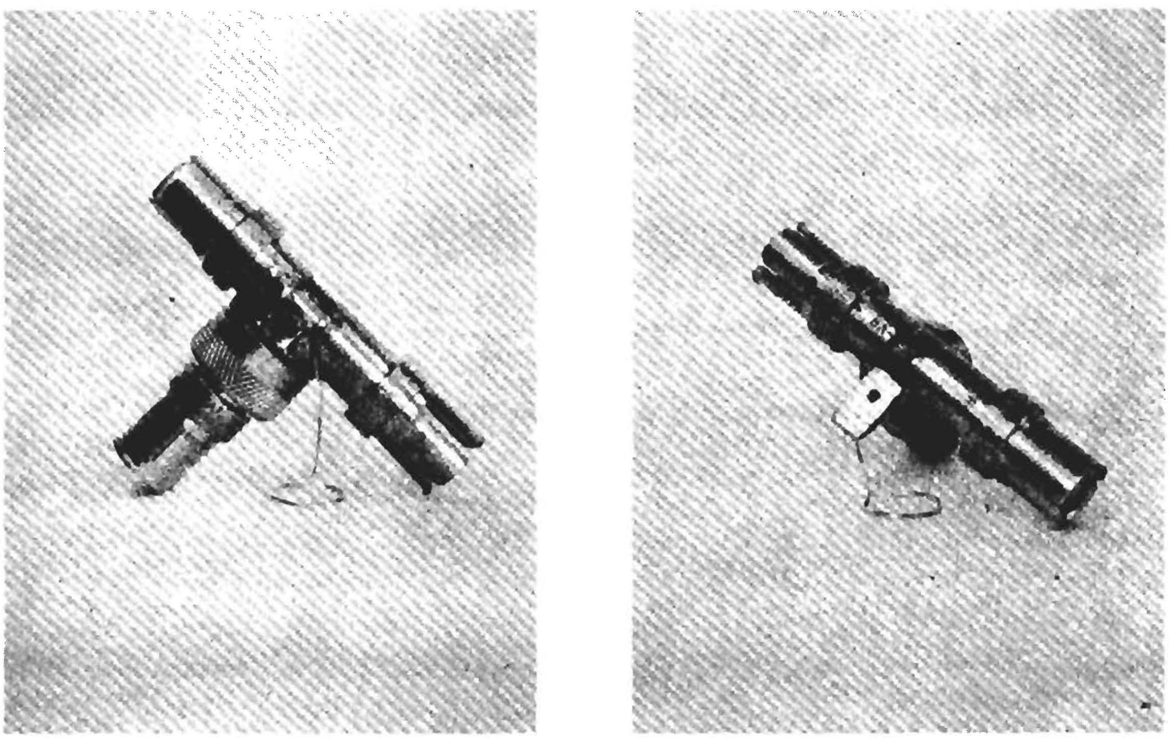
		Crystal Equivalent Resistance	
Crystal No.	Frequency (Mc/Sec)	Substitution Measurements (Ohms)	Standard Measurements (Ohms)
5	150	72	71
5	183	100	101
5	217	120	119
5	283	100	111
6	150	78	78
6	183	113	115
6	217	119	117
6	283	70	89
58	165	120	108
67	150	63	60
67	209	111	114
67	270	69	77
72	162	90	91
72	197	110	115
72	233	103	110
72	269	75	80

System were taken with a crystal dissipation of approximately one milliwatt while the data from the Crystal Substitution Measurements System were usually obtained at less than a 0.1 mw crystal dissipation.

Many of the laboratory crystals have developed leaks as a result of repeated insertion in test sockets. The leaks can account for resistance changes of several percent between the time of the Measurements Standard readings and the time of the substitution measurements.



A. FIRST PROTOTYPE MOUNT



B. SECOND PROTOTYPE MOUNT

Figure 62. Crystal Mounts for the Substitution Measurement System.

TABLE II

MINIMUM RESISTANCE AND CORRESPONDING FREQUENCY MEASUREMENTS OBTAINED WITH THE SUBSTITUTION MEASUREMENT SYSTEM AND WITH THE CRYSTAL MEASUREMENTS STANDARD SYSTEM

Crystal No.	Substitution Measurement System			Crystal Measurements Standard		Res. Error	Freq. Error
	Frequency (Mc/Sec)	Resistance (Ohms)	Power (Mw)	Frequency (Mc/Sec)	Resistance (Ohms)	(%)	(%)
5	150.2999	73	0.033	150.3004	69	5.7	0.00033
5	183.6984	104	0.043	183.6995	101	2.9	0.00060
5	217.0974	128	0.047	217.0991	119	7.5	0.00078
5	250.4957	131	0.10	250.4980	122	11.1	0.00092
5	283.8948	111	0.15	283.8965	112	-0.9	0.00060
6	150.3007	77	0.03	150.3015	77.2	-0.3	0.00053
6	183.7014	120	0.048	183.7015	117	2.5	0.00005
6	217.1018	120	0.039	217.1042	118	1.7	0.00110
6	250.5007	115	0.089	250.5027	112	2.7	0.00080
6	283.9006	89	0.16	283.9023	89	0.0	0.00060
MA-23	178.1872	159	0.065	178.1877	156	1.9	0.00028
MA-23	210.5828	187	0.078	210.5832	189	-1.1	0.00019
MA-23	242.9766	185	0.108	242.9787	182	1.6	0.00045
MA-23	275.3715	145	0.108	275.3725	144	0.7	0.00036
MA-24	178.1825	152	0.065	178.1845	152	0.0	0.00110
MA-24	210.5775	185	0.078	210.5789	185	0.0	0.00066
MA-24	242.9692	183	0.107	†	†	-	-
MA-24	275.3638	131	0.122	275.3663	127	3.1	0.00091
MA-25	178.1969	159	0.063	†	†	-	-
MA-25	210.5945	161	0.091	210.5960	159	1.3	0.00071
MA-25	242.9905	147	0.098	242.9915	147	0.0	0.00038
MA-25	275.3875	108	0.120	275.3880	109	-0.9	0.00018
MA-26	178.1887	124	0.082	178.1891	122	1.6	0.00022
MA-26	210.5845	147	0.099	210.5853	146	0.7	0.00038
MA-26	242.9781	161	0.100	242.9795	157	2.5	0.00058
MA-26	275.3719	133	0.110	275.3738	130	2.3	0.00069
MA-35	178.1817	156	0.062	178.1818	160	-2.5	0.00005
MA-35	210.5750	>200	0.068	210.5778	210	-	0.00130
MA-35	242.9666	192	0.052	242.9663	192	0.0	-0.00012
MA-35	275.3594	162	0.107	275.3605	159	1.9	0.00040
MA-36	178.1668	>>200	0.048	178.1671	410	-	0.00017

(Continued)

TABLE II (Continued)

MINIMUM RESISTANCE AND CORRESPONDING FREQUENCY MEASUREMENTS OBTAINED WITH THE SUBSTITUTION MEASUREMENT SYSTEM AND WITH THE CRYSTAL MEASUREMENTS STANDARD SYSTEM

Crystal No.	Substitution Measurement System			Crystal Measurements Standard		Res. Error	Freq. Error
	Frequency (Mc/Sec)	Resistance (Ohms)	Power (Mw)	Frequency (Mc/Sec)	Resistance (Ohms)	(%)	(%)
MA-37	178.1866	144	0.069	178.1872	144	0.0	0.00034
MA-37	210.5806	192	0.082	210.5824	175	9.7	0.00086
MA-37	242.9729	>200	0.050	242.9738	202	-	0.00037
MA-37	275.3639	167	0.094	275.3640	180	-7.3	0.00004
MA-58	164.9976	118	0.092	164.9987	108	9.3	0.00067
MA-58	194.9958	147	0.075	194.9977	133	10.5	0.00098
MA-58	224.9919	147	0.127	224.9935	155	-5.4	0.00071
MA-58	254.9898	137	0.140	254.9923	139	-1.5	0.00098
MA-58	284.9851	93.5	0.200	†	†	-	-
FA-67	149.9825	61	0.054	149.9849	60	1.7	0.00160
FA-67	209.9764	113	0.126	209.9766	114	-0.9	0.00009
FA-67	269.9681	78	0.157	269.9683	77	1.3	0.00007
FA-106	165.0601	46.5	0.057	165.0630	44	5.7	0.00170
FA-106	231.0846	45	0.230	231.0845	43	4.7	-0.00004
FA-106	297.1026	<<35	0.240	297.1023	26	-	-0.00010
FA-115	175.0703	37	0.067	175.0721	37	0.0	0.00100
FA-115	245.1034	40	0.100	245.1034	38	5.2	0.00000

†Data not available because a spurious response was measured.

An examination of the crystal data has indicated that some of the crystals may not have been firmly seated in the component mount when the original Crystal Measurements Standard runs were made. A change in the lineal position of the cyrstal by 0.12 cm in the component mount of the Crystal Measurements Standard has recently been found to change the equivlent resistance by 7 percent. A similar source of error in equivalent-resistance determination was observed with the Substitution Measurements System mount.

d. Modifications of the Substitution Measurement Mount. Further work to improve the accuracy of the Substitution Measurements System was continued. A study of the possible causes of error has indicated that the major source of conductance measurement error was the placement of the crystal with respect to the center conductor of the component mount. The reference plane of the Crystal Measurements Standard System is perpendicular to the pins and tangent to the base of the crystal unit. For best data agreement, an identical mount should be used for the Substitution System; however, the nature of the Substitution System prohibits this arrangement.

With either the Measurements Standard System or the Substitution Measurement System, the physical spacing between the crystal base and the measurement plane greatly affects the resulting data. The mount of the Measurements Standard System has been standardized so that the measurement plane is in contact with the crystal base. With the first and second prototype mounts for the Substitution System the spacings between the measurement plane and crystal base were approximately 0.2 cm and 0.1 cm, respectively.

The spacing between the crystal base and the measurement plane for the second mount could not be appreciably reduced without shorting the center conductor of the mount to the crystal can. However, because of the compound curvature of the center conductor of the first mount, the spacing between the point of contact with the crystal pin and the base of the crystal could be made negligible. Also, the physical construction of the first mount more closely resembled that the Measurements Standard System mount.

The first prototype mount (Figure 62A) was rebuilt by recessing the grounded pin connector so that the crystal base would be in contact with the measurement plane. The second connection to the center conductor was provided by drilling two intersecting holes as shown in Figure 63. A metal plunger and spring were inserted into the hole along the conductor axis as shown. The other hole was made smaller than the hole along the axis and only slightly larger than the crystal pin so that the spring pressure could provide good electrical and mechanical connections. The holes, because of their small diameters, should not appreciably affect the impedance of the transmission line.

The position of the crystal in the mounts causes only relatively small errors in the measurement of the crystal resonant frequency and thus cannot account for the frequency errors shown in Table II. Remeasurements of both the substitution data and the Measurements Standard data indicated that the major portions of the errors were due to crystal parameter changes. The Measurements Standard data had been obtained several months previously. During the intervening time, the crystals had aged and some had even developed small vacuum leaks. The room temperature during the Standard runs was 70°F or less compared to about

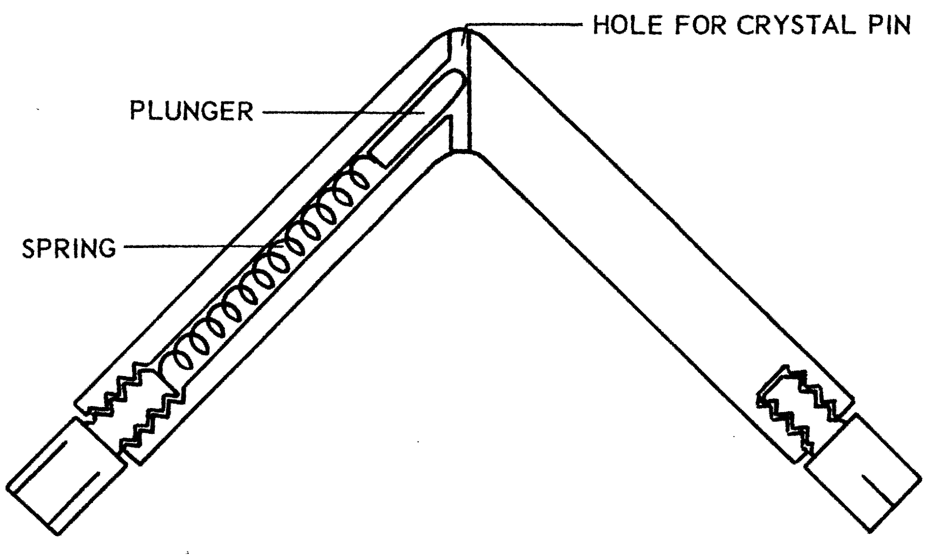


Figure 63. Cross-Section View of the Center Conductor of the Substitution Mount.

95°F during the substitution measurements. These factors resulted in appreciable changes in the resonant frequencies of the crystals. In some cases, the changes were compensating and resulted in accuracies better than the normal capabilities of the equipment. To obtain a valid comparison, the crystals must be measured by both systems at approximately the same time and under as nearly identical conditions as possible.

The Measurements Standard data were rerun by setting up the Admittance Meter for half-wavelength line measurements at each crystal overtone response to eliminate the digital computer calculations. The maximum conductances were determined by varying the signal generator frequency, obtaining a null, observing the conductance, and then changing the frequency by a small increment. This process was repeated until the maximum conductance was found. The conductance and frequency were then recorded. Corresponding measurements were then obtained with the substitution system. The approximate time required for the Measurements Standard data was 20 to 30 minutes per response compared to about 3 minutes per response for the substitution system.

Table III shows a comparative summary of the measurements by the two methods. The maximum error in the substitution resistance measurements is less than 4 percent and the maximum error in the substitution frequency measurements is less than 0.0002 percent with respect to the Measurements Standard System data.

Shortly after the above data were obtained, the crystal diode of the crystal mount became defective because of stress resulting from repeated insertion of the crystals and resistors. The body of this diode was in contact with the crystal at one point when the crystal was properly positioned in the mount. When the defective diode was replaced, a different mounting procedure was employed. The diode was recessed further into the mount, as

TABLE III

MINIMUM RESISTANCE AND CORRESPONDING FREQUENCY MEASUREMENTS OBTAINED WITH THE SUBSTITUTION MEASUREMENT SYSTEM AND WITH THE CRYSTAL MEASUREMENTS STANDARD SYSTEM

Crystal No.	Substitution Measurement System		Crystal Measurements Standard		Res. Error	Freq. Error
	Frequency (Mc/Sec)	Resistance (Ohms)	Frequency (Mc/Sec)	Resistance (Ohms)	(%)	(%)
5	217.0975	127	217.0976	125	+1.6	-0.00005
5	250.4960	130	250.4959	129	0.8	0.00004
5	283.8947	106	283.8949	105	1.0	-0.00007
6	217.1018	116	217.1015	115	0.9	0.00014
6	250.5010	110	250.5008	109	0.9	0.00008
6	283.9009	85	283.9007	85	0.0	0.00007
MA-23	178.1870	154	178.1872	149	3.4	0.00011
MA-23	210.5827	187	210.5827	182	2.8	0.00000
MA-23	242.9769	170	242.9766	167	1.8	0.00012
MA-24	178.1822	149	178.1825	145	2.8	-0.00017
MA-24	210.5771	177	210.5772	172	2.9	-0.00005
MA-24	242.9690	164	242.9690	162	1.2	0.00000
MA-25	178.1970	150	178.1970	153	-1.9	0.00000
MA-25	210.5948	153	210.5948	155	-1.3	0.00000
MA-25	242.9902	143	242.9905	143	0.0	-0.00012
MA-26	178.1886	122	178.1887	119	2.5	-0.00006
MA-26	210.5846	139	210.5843	141	-1.4	0.00015
MA-35	178.1818	155	178.1818	157	-1.3	0.00000
MA-35	210.5752	182	210.5754	185	-1.6	-0.00010
MA-37	178.1868	140	178.1867	139	0.7	0.00006
MA-37	210.5807	172	210.5807	175	-1.7	0.00000
FA-67	269.9675	72	269.9670	72	0.0	0.00018

may be seen in Figure 64 so that no contact could be made with the crystal unit.

The characteristics of the new diode were essentially the same as those of the original unit. A large part of the original data was rerun to verify this.

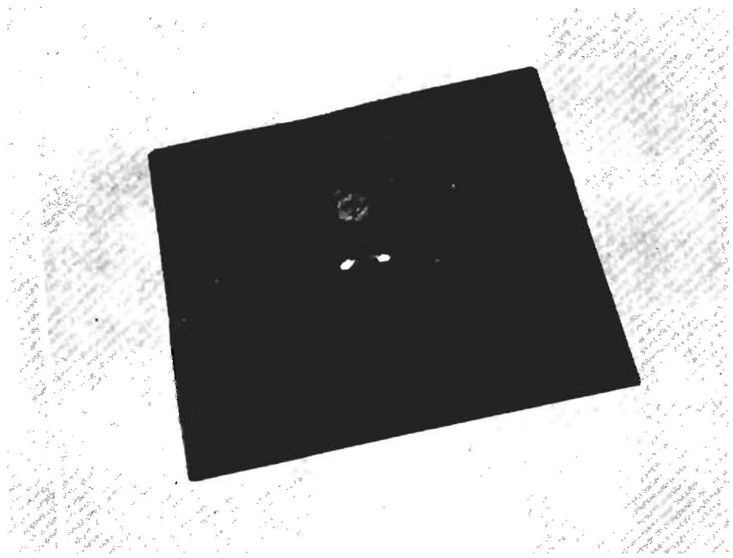


Figure 64. Crystal Mount for the Substitution Measurement System.

Another crystal mount essentially identical to that shown in Figure 64 was constructed and sent to USASRDL for evaluation.

e. Measurement Data and Analyses. Complete substitution measurement data were obtained for 12 crystal overtone responses between 200 and 300 mc/sec. The data are shown in Table IV.

For comparison purposes, the Crystal Measurements Standard System was used to obtain data comparable to the substitution data. The Standard System is capable of providing data for the calculation of actual crystal Q; however, the calculations are very involved. Also, the comparison of Q' with Q would not separate the measurement error of the Substitution System from the inherent error due to the way in which Q' is defined. Thus, the Standard System was used to determine only the values of admittance of f_r, f_1, and f_2. A half-wavelength line was used between the Admittance Meter and the crystal mount so that direct

TABLE IV

COMPARISON OF RESISTANCE AND Q' MEASUREMENTS

Crystal No.	Substitution Measurement System: Frequency (Mc/Sec) f_r	f_1	f_2	G_{max} (Millimhos)	G_{min} (Millimhos)	R_{min} (Ohms)	Q'	Crystal Measurement Standard: R_{min} (Ohms)	Q'	Error (%R)	Error (%Q')
FA-67	209.9767	209.9731	209.9807	9.1	1.0	110	10,100	109	9,600	+0.9	+5.0
MA-23	210.5832	210.5817	210.5845	5.6	1.0	179	25,300	183	23,700	-2.2	+6.6
No. 5	217.0985	217.0974	217.0994	8.3	1.0	123	33,100	123	33,200	0.0	-0.3
No. 6	217.1022	217.1007	217.1039	8.6	1.0	117	24,800	116	27,400	+0.9	-8.9
No. 12	219.9821	219.9810	219.9833	7.4	1.1	134	34,900	129	28,000	+3.9	+22.0
FA-104	230.9356	230.9340	230.9374	14.0	2.3	71.5	24,100	71.0	23,600	+0.7	+2.4
FA-115	245.1036	245.0997	245.1066	25.5	3.6	39	14,300	39	13,600	0.0	+4.8
3-W	274.5305	274.5287	274.5321	14.2	2.4	70.4	28,500	69.6	28,000	+1.2	+2.0
FA-91	279.0407	279.0386	279.0427	23.6	2.7	42.4	26,800	41.0	24,800	+3.4	+7.9
No. 5	283.8949	283.8918	283.8971	9.6	2.5	104	16,100	104	13,000	0.0	+23.7
No. 6	283.9009	283.8983	283.9032	12.1	2.8	82.7	18,400	82.0	14,800	+0.9	+24.4
FA-105	296.8921	296.8893	296.8946	23.1	6.0	43.2	18,000	41.8	17,600	+3.3	+3.0

admittance readings would be obtained without the use of a digital computer. The half-wavelength line reduced the accuracy of the data slightly. The crystal drive level, as indicated by an r-f voltmeter, was kept small and approximately the same in both measurement systems.

Previous data had indicated that the substitution system could determine the resonant frequency, f_r, with approximately the same accuracy as the Standard System; however, this indication was again verified by changing the frequency slightly during the Standard System measurements to determine if a greater G_{max} could be found. For the 12 responses measured, the values remained the same. Both conductance (G_r or G_{max}) and susceptance (B_r) were recorded at the frequency f_r.

Conductances and susceptances at frequencies f_1 and f_2 were then measured (G_1 and B_1 at f_1; G_2 and B_2 at f_2). The minimum conductance, G_{min}, was not measured with the Standard System because of the time involved.

All of the data were corrected on the Admittance Meter correction charts. The resonant susceptance, B_r, was subtracted from the susceptance at each of the three frequencies to simulate antiresonating the crystal. If

$$B_1' = B_1 - B_r, \; B_2' = B_2 - B_r$$

and

$$\Delta\theta = \text{ArcTan}\,\frac{B_1'}{G_1} + \text{Arc Tan}\,\frac{-B_2'}{G_2} \quad ,$$

then

$$Q' = \frac{f_r}{2}\left(\frac{\Delta\theta}{f_2 - f_1}\right) \quad .$$

The Standard System measured and calculated data are also shown in Table IV.

At some of the responses, the current data were compared with circle diagram data, which had been obtained previously, to determine the angle ϕ. In each case the angle was found to be between 40 and 50 degrees, as predicted by theory.

In all cases, the error in the determination of R_{min} by substitution measurements was less than ± 4 percent with respect to the Standard System data. The disagreement in Q' was less than ± 10 percent in all except three cases. In these three cases, poorer accuracy was expected due to the poor crystal overtone responses.

Information about the quality of a crystal response can be obtained while steps 1 and 2 are being performed by observing the oscillographic patterns of the crystal responses. Typical responses are shown in Figure 65. Figure 65(a) shows a relatively-spurious-free, low-resistance, high-Q response. Figure 65(b) is a response which is equally spurious-free but which has higher resistance and thus lower Q. Poorer accuracy may be expected in determining the value of Q for this response due to the gradual slope of the sides of the response. Figure 65(c) shows a low resistance but highly distorted response. The distortion is produced by the lossy crystal holder as was described for a theoretical crystal in the Final Report of Contract No. DA-36-039 SC-78910. At higher frequency responses, the distortion would become more severe. At frequencies near the holder resonant frequency, the response would be essentially the inverse of Figure 65(a) or 65(b). Figure 65(d) shows a crystal response with a spurious response occurring very near the main response. Calculation of Q by the substitution method is very difficult for a response of this type. Figure 65(e) shows a crystal with spurious response of lower resistance than the main response. The separation between the two responses is adequate; however, the

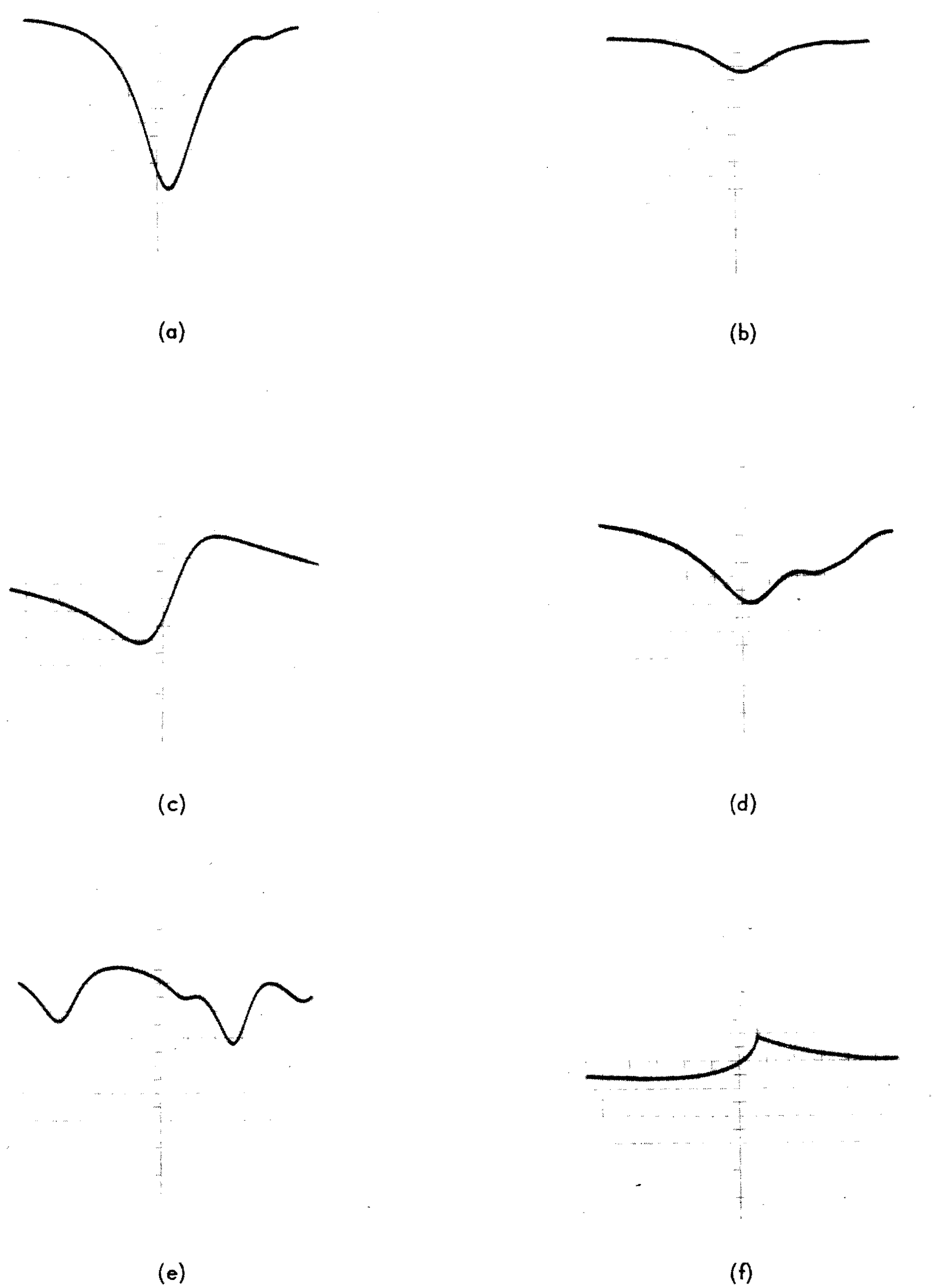


Figure 65. Typical Sweep Display with the Substitution Measurement System.

usefulness of such a crystal would be questionable. Figure 65(f) shows two phenomena. First, the response is inverted as mentioned above. Second, a discontinuity occurs because of excessive drive level.

Of the responses of Figure 65, only Figure 65(a) represents a completely satisfactory crystal. The Substitution Measurements System, however, is capable of determining G_{max} and G_{min} for any crystal response. Figure 61 shows the region where each resistance is measured for the ideal response of Figure 65(a). Where discontinuities occur, such as in Figure 65(f), the maximum and minimum resistance values are completely meaningless.

The crystal Q may be measured, by use of the procedure described previously, for most of the responses of Figure 65, but will be meaningful only for responses similar to that of Figure 65(a) and possibly 65(b) and 65(c). This restriction is not considered to be severe since only the response of Figure 65(a) can be used to satisfactorily control the frequency of current oscillator types.

f. A Complete High-Frequency Crystal Impedance Meter. The Substitution Measurements System as discussed in the previous sections may be used as the basis for a high-frequency Crystal Impedance Meter. The instrument could be completely self-contained, including provisions for determining frequency. A typical block diagram is shown in Figure 66. The Sweep-Frequency Synthesizer should be capable of generating any frequency in the range from 150 to 300 mc/sec with provisions for frequency deviation from zero to at least 25 kc/sec. The generated frequency should be known to better than one part in 10^6. The output must be relatively free of spurious frequencies. Problems might be encountered in packaging the device in a sufficiently small space.

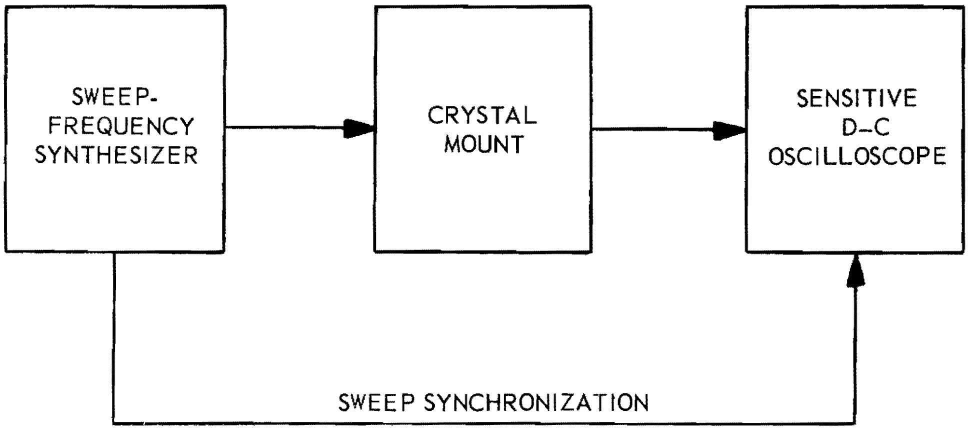


Figure 66. A Prototype High-Frequency Crystal Impedance Meter.

The Crystal Mount of Figure 66 would be similar to those described in the previous sections and would include the shorted stub necessary to antiresonant the crystal under test.

The Sensitive D-C Oscilloscope should have a vertical d-c sensitivity of approximately 3 mv/cm and a stability of better than 0.1 mv/min. Only one sweep speed would be required but the sweep must be synchronized with the sweep of the synthesizer. A 3-inch-diameter oscilloscope tube should be adequate if an auxiliary meter were used for final adjustments.

For production crystal testing, such an instrument could be precalibrated so that the use of substitution resistors would not be necessary. Zones of acceptance could be marked on the oscilloscope as shown in Figure 67. In this figure, the bottom of the first minimum must fall in Zone 1 for the maximum conductance and frequency to be within acceptable limits. The spurious responses, to be acceptable (not too close to the main response and of sufficiently small conductance), must fall within Zone 2. The base line of the response must fall above Acceptance Line 1 to insure that the minimum crystal conductance is sufficiently small. The acceptable range of susceptive-component

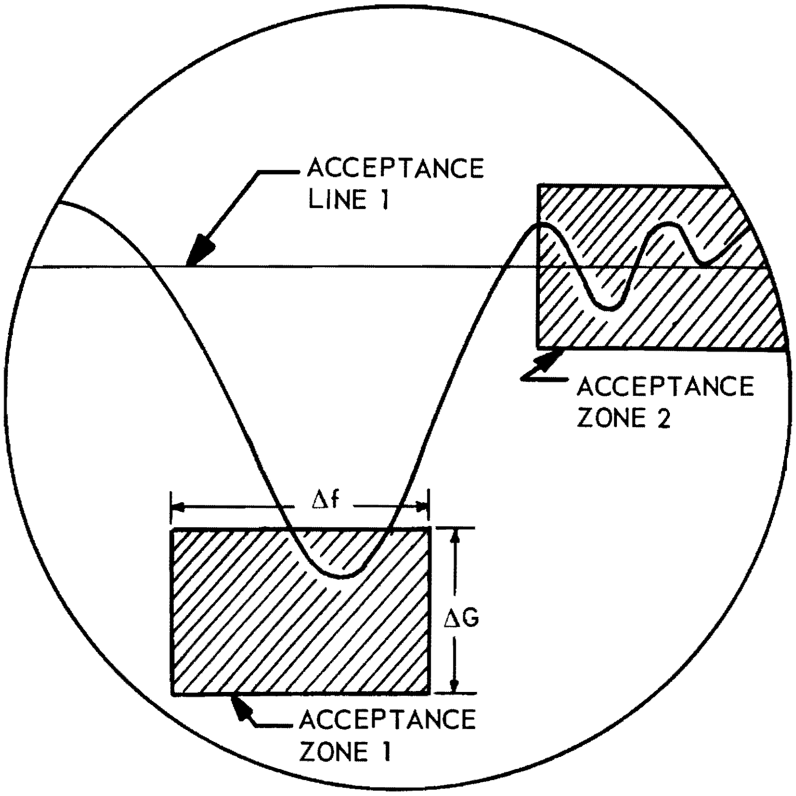


Figure 67. Typical Zones of Acceptance for Production Crystals.

values could be marked on the shorted stub. An acceptance on the basis of Q could be decided from the slope of the sides of the main response.

3. Crystal Characteristics

a. Drive Level Effects. Various parameters of quartz crystals are known to be affected by the degree to which the crystal is electrically driven. These effects have been examined to determine the possible errors of the Crystal Measurements Standard System and of the Substitution Measurement System due to the lack of precise drive level control.

As has been previously mentioned, the crystal drive level was kept small and approximately the same for both measurement systems. The sensitivities of both systems permitted measurements to be made with drive levels as small as 0.01 mw. Typical measurements were made at a level of about 0.1 mw. The drive level for the substitution measurement system was estimated from predetermined r-f voltage versus d-c voltage calibrations of the crystal mount diode. The drive level for the Crystal Measurements Standard System was estimated from r-f voltage measurements at the component mount at high drive levels. The attenuator on the Marconi Signal Generator was then used to reduce the drive level by the desired amount.

Typical measurements indicated that the drive level did not appreciably affect the values obtained for G_{max} or G_{min}. To determine the frequency effects, one crystal response (FA-91 at 279 mc/sec) was examined in the Crystal Measurements Standard System at three drive levels, 0.01, 0.1 and 1.0 mw. The conductance and susceptance curves at each drive level are shown in Figure 68. A Smith Chart diagram of the same data is shown as Figure 69. The departure of points from the circle of Figure 69 is within the accuracy of the Standard System since a half-wavelength rather than a short line was used between the Admittance Meter and the component mount. As may be observed from the figures, the values of G_{max}, G_{min}, and Q' of the crystal are affected very little by the drive level variations; however, the variations in frequency are relatively much more noticeable. (Here, the relative importance of each variation is based upon the desired and obtainable measurement accuracy of each parameter. If absolute measurements could be made, the effects of drive level on frequency might well be much less, by percentage, than the effects on other quantities.)

Similar variations were observed with the substitution measurement system as a function of drive level. The frequencies at maximum conductance, f_r, are

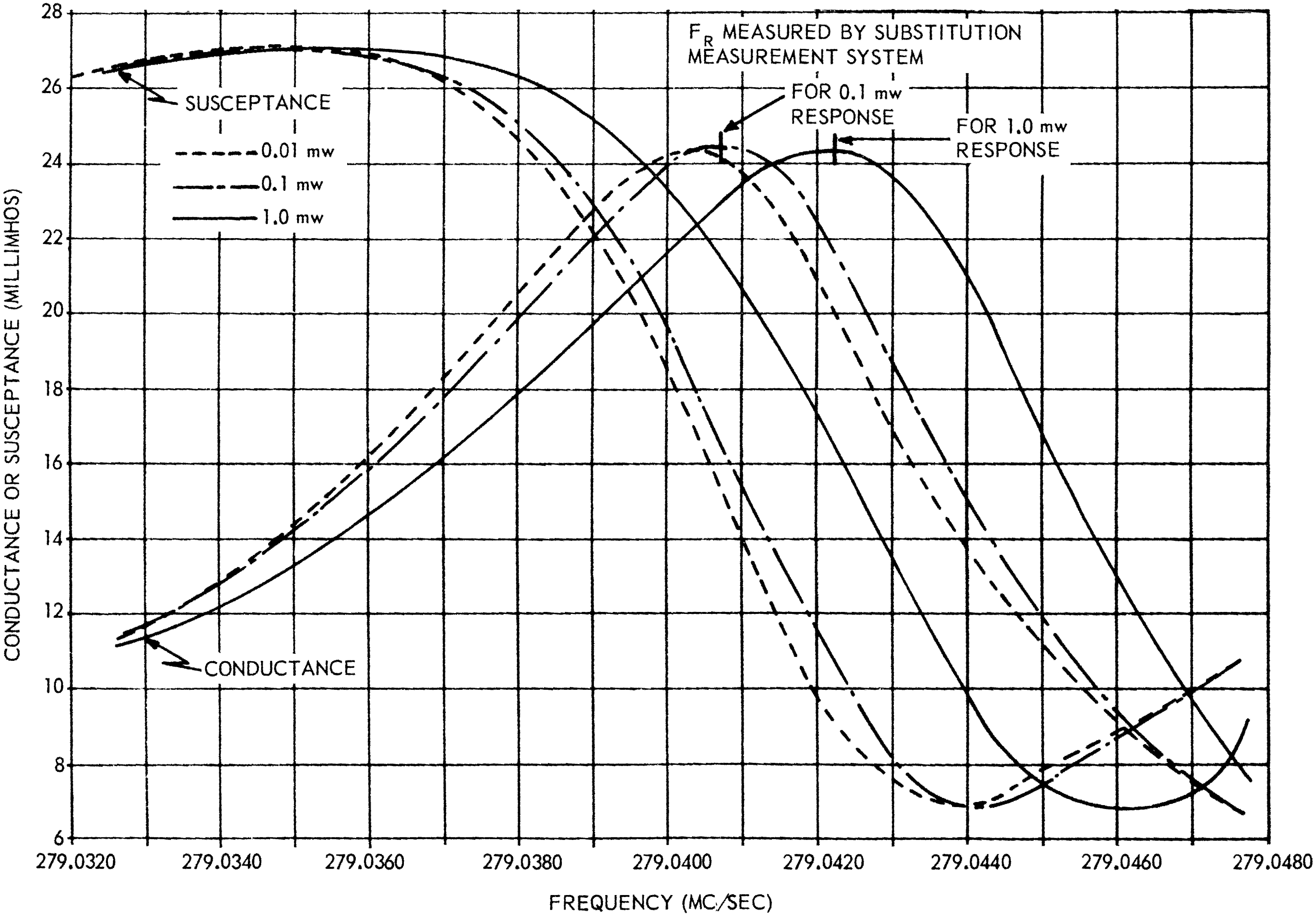


Figure 68. Effects of Drive Level on Crystal Frequency Characteristics.

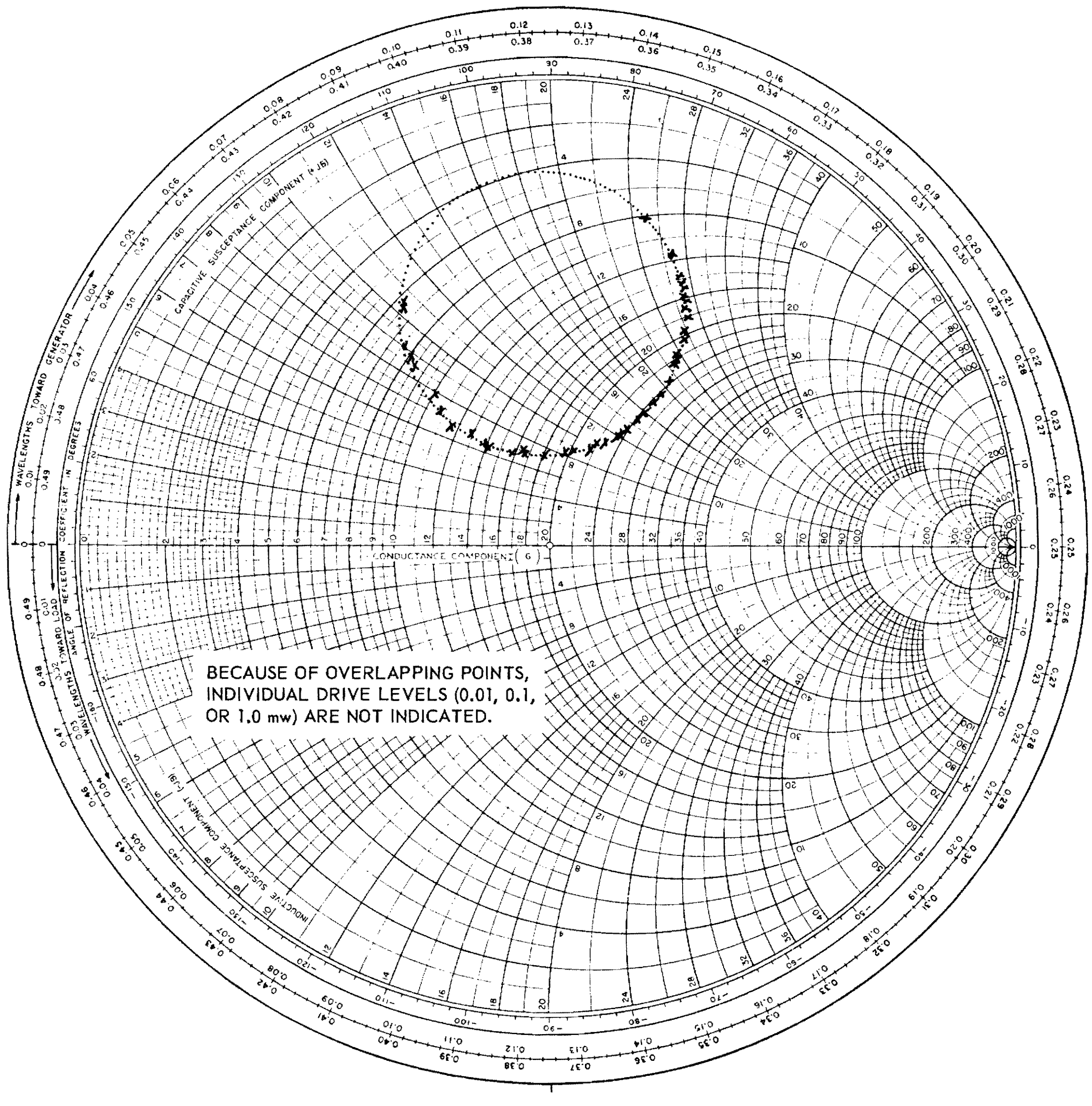


Figure 69. Effects of Drive Level on Crystal Admittance Characteristics.

marked on Figure 68 for two drive levels.

To minimize the drive level effects, the measurements described in the previous section were made at drive levels of less than 0.1 mw. Drive levels were also kept approximately the same for the two measurement systems.

b. Temperature Characteristics. During the initial investigations of crystal-controlled vacuum-tube oscillator circuits, frequency variations which could be correlated with ambient temperature variations were observed. In these circuits, precise temperature control of the crystal was not possible because of the short leads required for proper oscillator operation and because of the large amount of heat dissipated by the circuit (typically 5 watts). A knowledge of the frequency-temperature characteristics of the crystals was thus desirable.

The procedure for determining the frequency-temperature characteristics of crystals consisted of heating the crystals in a small crystal oven, measuring the temperature by means of a thermocouple, and measuring the frequency with the Substitution Measurement System. A suitable thermocouple was prepared from 32-gauge Advance Alloy Driver Harris wire and 34-gauge copper wire. The temperature calibration of such a thermocouple is given in Table V. A Leeds and Northrup portable precision potentiometer was used to measure the output voltage.

The crystal, whose characteristics were to be determined, was placed in a modified James Knights Model JK09S crystal oven. The modifications to the oven consisted of shorting the thermostat terminals, providing a base plug to fit the substitution crystal mount and providing a hole in the top of the case for the thermocouple wires. The thermocouple wires were soldered directly to the crystal can.

TABLE V

THERMOCOUPLE TEMPERATURE CALIBRATION FOR
32-GAUGE ADVANCE ALLOY DRIVER HARRIS AND 34-GAUGE COPPER WIRES

Temperature (°C)	Output (Mv)	Temperature (°C)	Output (Mv)	Temperature (°C)	Output (Mv)
25	0.918	51	1.929	76	2.950
26	0.956	52	1.969	77	2.992
27	0.994	53	2.009	78	3.034
28	1.032	54	2.049	79	3.076
29	1.070	55	2.089	80	3.117
30	1.109	56	2.130	81	3.160
31	1.147	57	2.170	82	3.202
32	1.185	58	2.210	83	3.244
33	1.224	59	2.251	84	3.287
34	1.262	60	2.291	85	3.329
35	1.301	61	2.332	86	3.371
36	1.339	62	2.373	87	3.414
37	1.379	63	2.414	88	3.457
38	1.417	64	2.454	89	3.499
39	1.456	65	2.495	90	3.542
40	1.495	66	2.536	91	3.585
41	1.534	67	2.577	92	3.628
42	1.573	68	2.618	93	3.671
43	1.613	69	2.660	94	3.714
44	1.652	70	2.701	95	3.756
45	1.691	71	2.742	96	3.800
46	1.730	72	2.784	97	3.843
47	1.770	73	2.825	98	3.886
48	1.810	74	2.867	99	3.930
49	1.850	75	2.908	100	3.973
50	1.889				

An adjustable a-c voltage was applied to the oven heater so that the oven temperature could be increased or decreased at any desired rate and so that the temperature could be held relatively constant at any desired temperature.

The test crystal is displaced by about 3 cm from the substitution component mount by the internal lead length of the oven. The resonant frequency of the crystal cannot, therefore, be directly measured. However, distinct voltage maximums and minimums are still obtained with the Substitution Measurement System. Any of these maximums or minimums may be used to determine the frequency-temperature characteristic. Since the spurious responses could have coefficients which are slightly different from that of the main response, the main or lower frequency response is generally chosen for the measurements.

The shape of an overtone response was observed on the oscilloscope of the Substitution Measurement System as the temperature was varied over a wide range. No noticeable change in the shape occurred. Thus any maximum or minimum of voltage can be expected to have the same frequency dependence on temperature as the resonant frequency.

A photograph of the equipment used for measuring the temperature coefficients is shown in Figure 70. The block diagram of the equipment is shown in Figure 71. The procedure consists of adjusting the Variac to some small output voltage and then permitting the oven temperature to stabilize. The

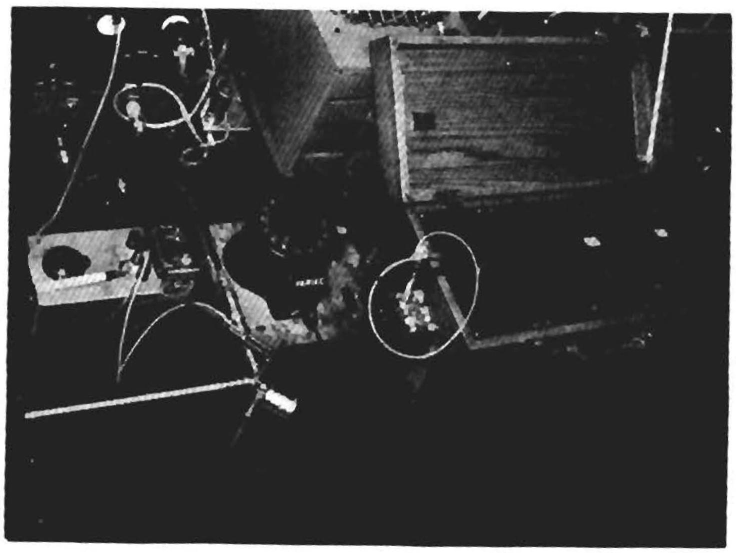


Figure 70. Photograph of the Crystal Temperature-Coefficient Measurement Setup.

thermocouple voltage is read from the potentiometer and the reference temperature of the potentiometer is observed. The frequency is read by reducing the

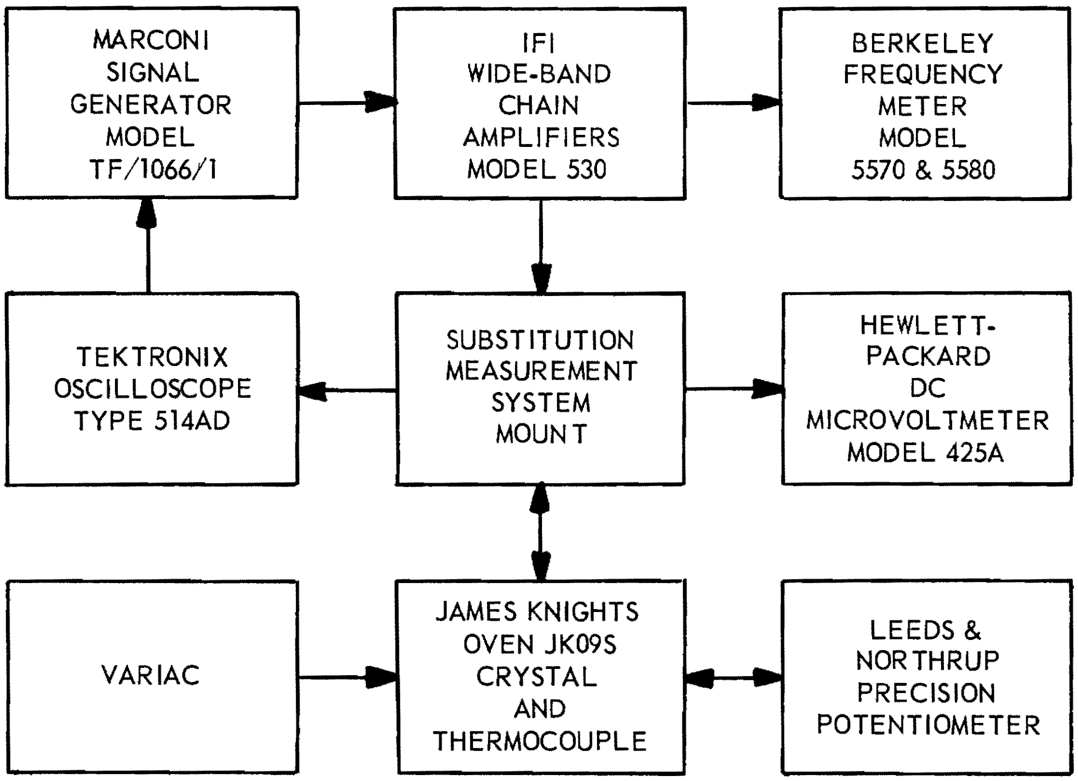


Figure 71. Block Diagram of the Crystal Temperature-Coefficient Measurement Set-Up.

sweep to zero deviation while adjusting the Signal Generator to the desired maximum or minimum. All data are recorded and the voltage of the Variac is again increased.

To determine the time required for the oven temperature to stabilize, a data run was made for one crystal by increasing the temperature rapidly to a temperature of 75°C, permitting the oven to stabilize for 20 minutes at this temperature, and then decreasing the temperature by removing all voltage from the crystal oven. The open loop characteristic of Figure 72 was obtained. The crystal frequency changed by only a small amount during the stabilization period at 75°C because of the approaching flat portion of the curve. The true temperature characteristic of the crystal must lie within the open loop and can be obtained for either increasing or decreasing temperature (the same curve will be obtained in either case) by permitting adequate time for stabilization at each temperature. A time of 8 minutes was found to be more than adequate for this purpose. Thus, a time of 8 minutes was permitted for stabilization at each temperature for each of the characteristics recorded.

The characteristics for several additional crystals are shown in Figures 73, 74, 75, and 76. For a few of the crystals, temperature runs were made for two overtone frequencies spaced over the expected frequency range of interest. The frequency change in parts per million per degree Centigrade was found to be approximately the same at each overtone frequency for any particular crystal. Therefore, only one temperature run was made for most of the crystals. An overtone frequency was chosen somewhere near the middle of the frequency range of interest.

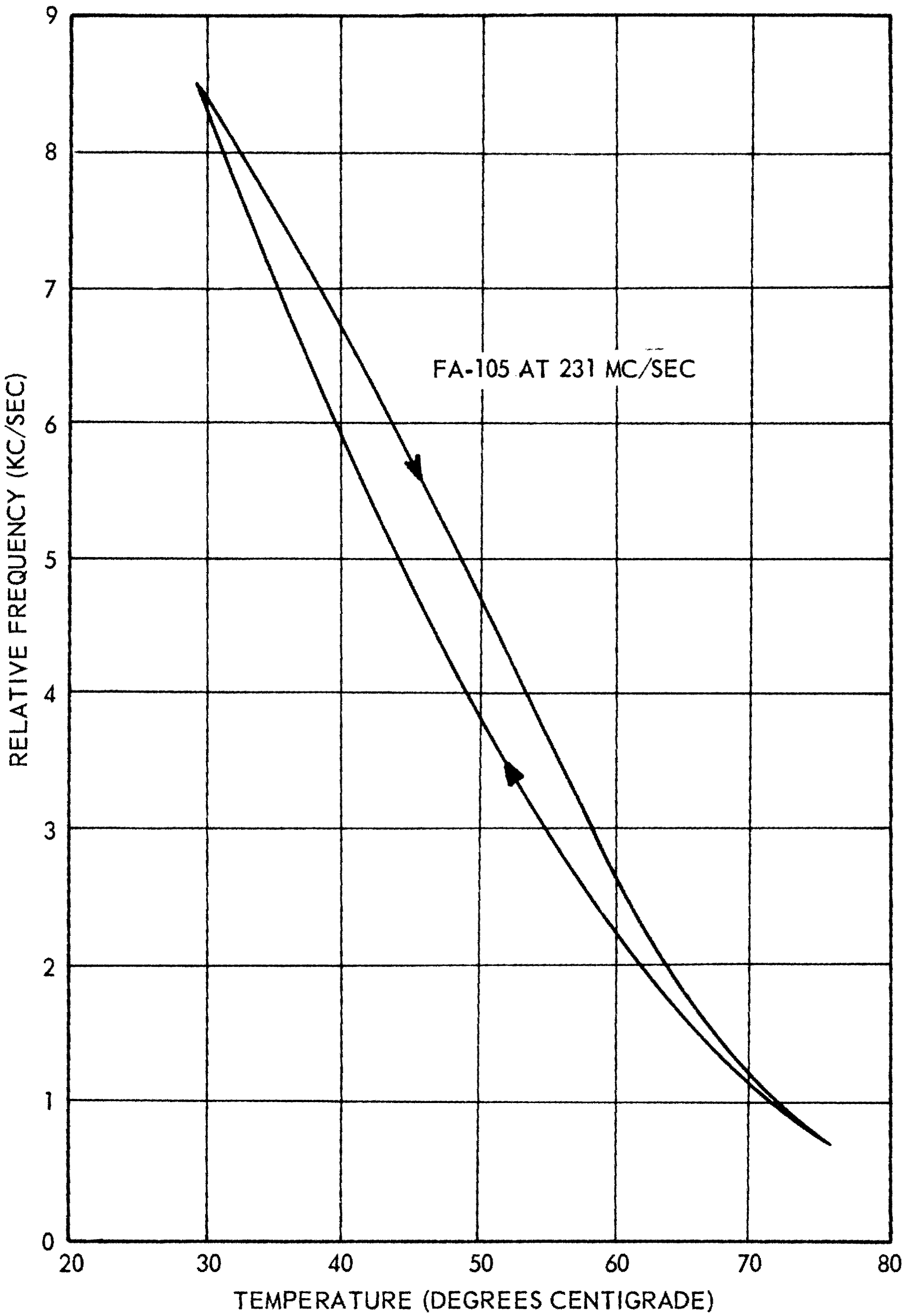


Figure 72. Temperature Coefficient of Crystal FA-105.

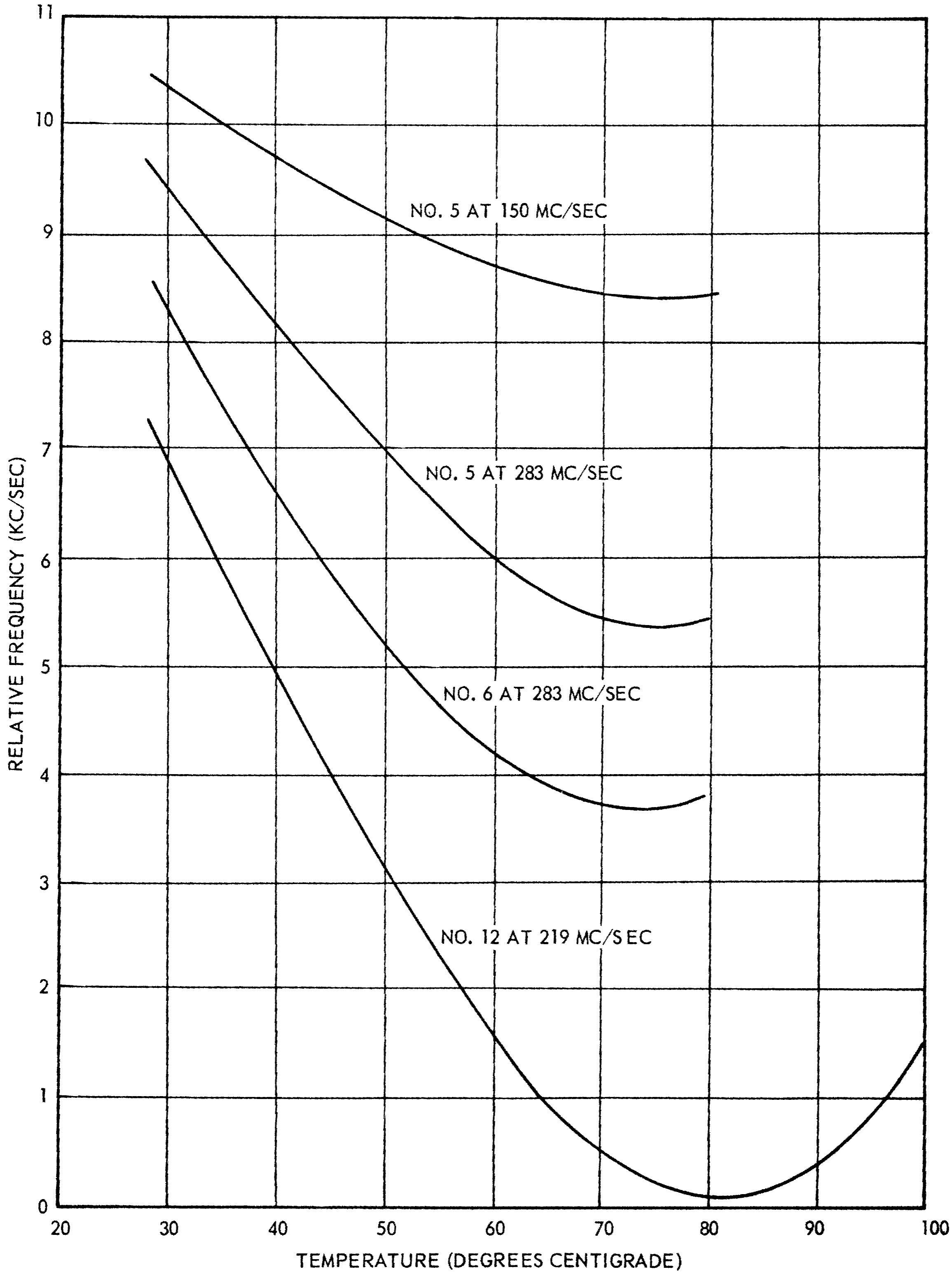


Figure 73. Temperature Coefficients of Crystals 5, 6, and 12.

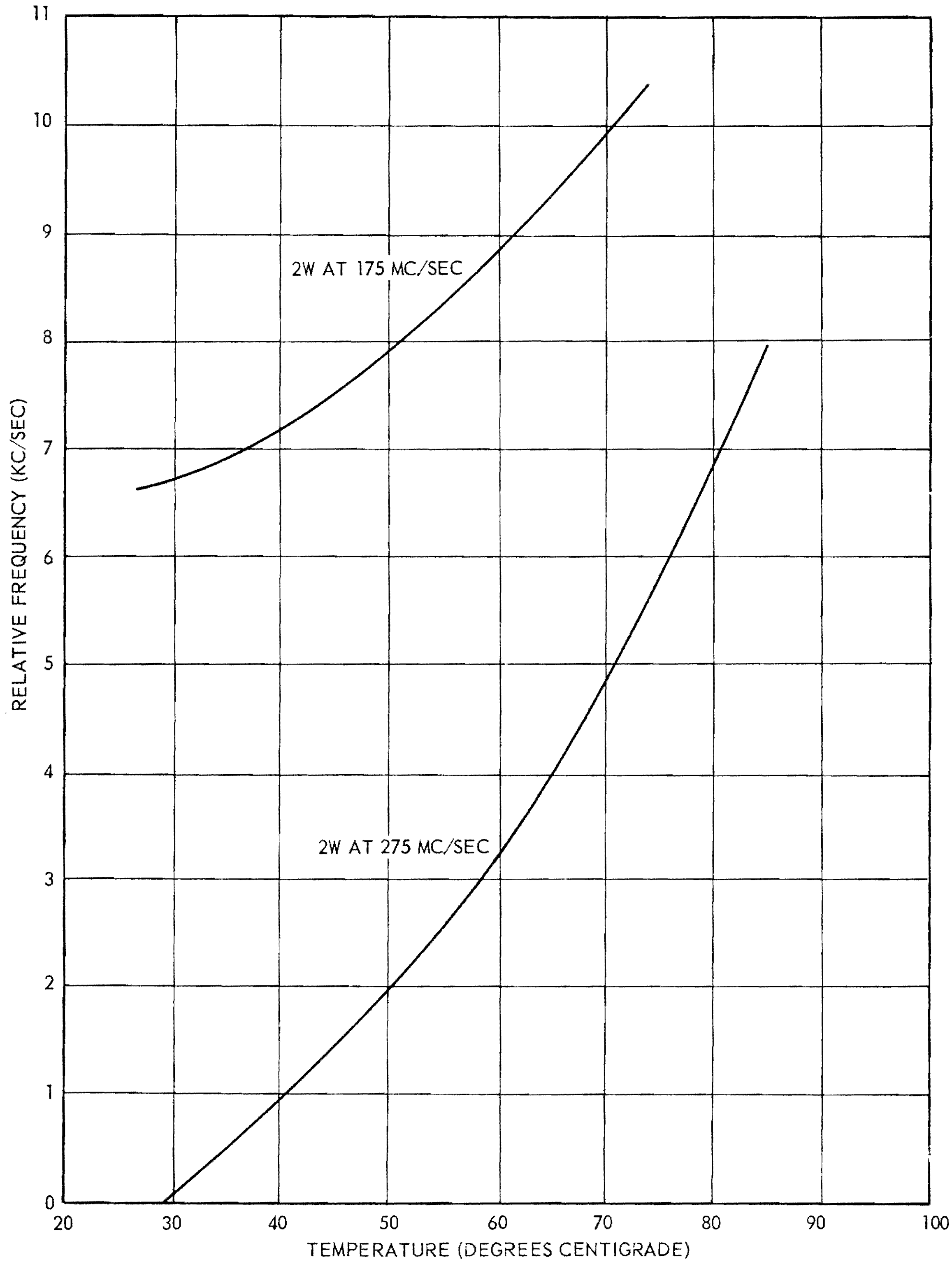


Figure 74. Temperature Coefficient of Crystal 2W.

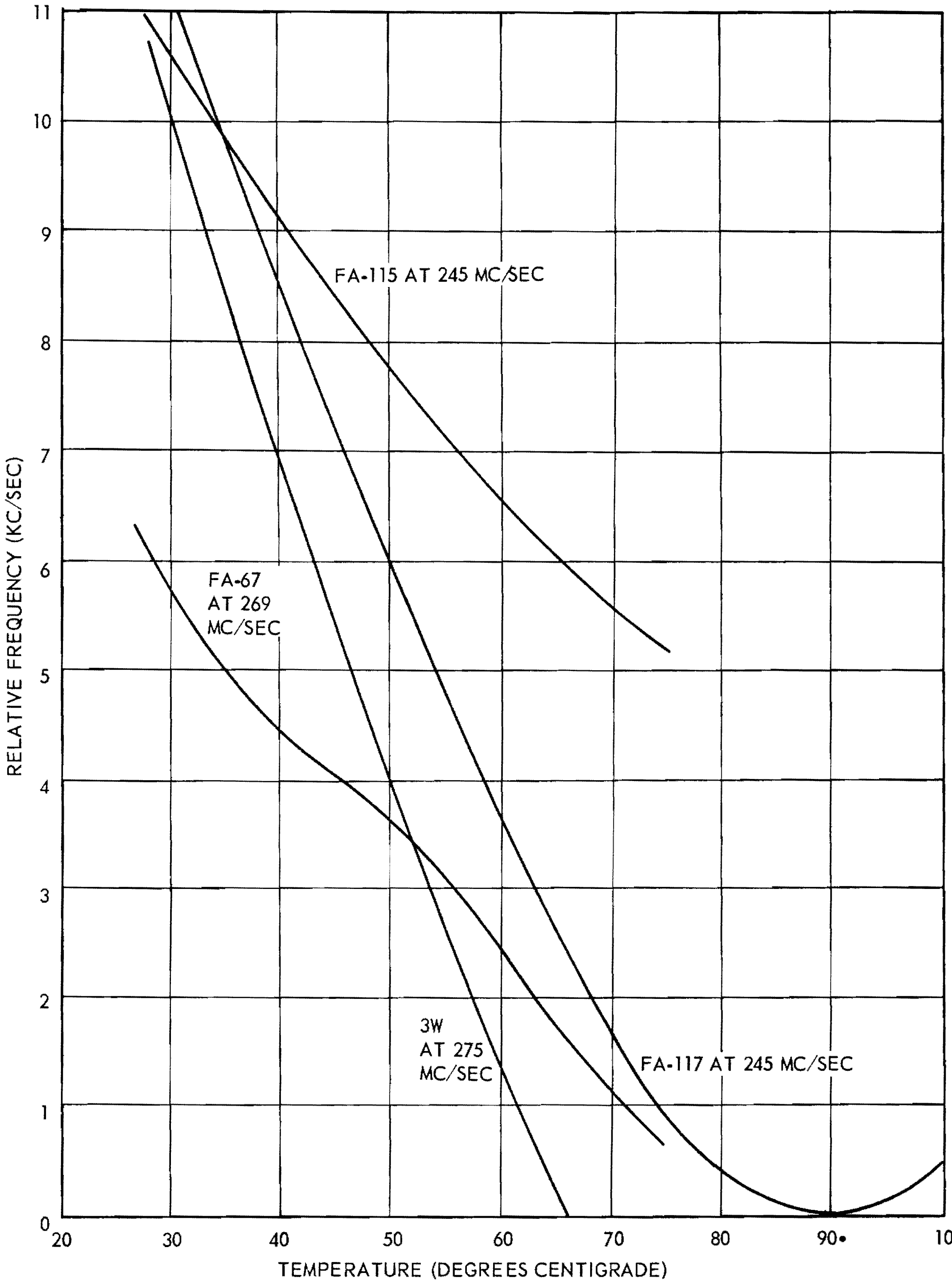


Figure 75. Temperature Coefficient of Crystals FA-67, FA-115, and FA-117.

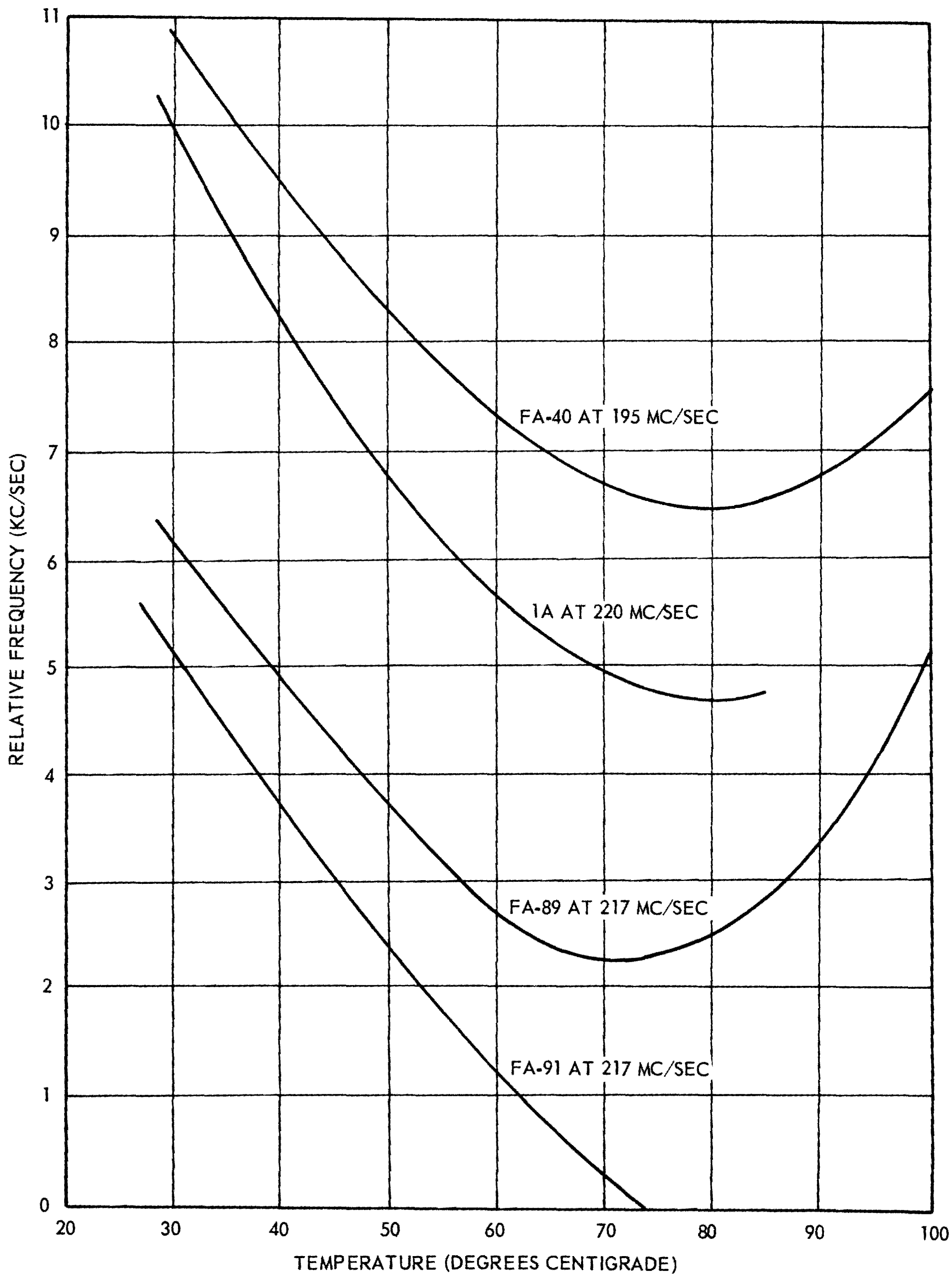


Figure 76. Temperature Coefficients of Crystals FA-40, FA-89, FA-91, and 1A.

All of the crystals except one (crystal 2W) showed a negative frequency-temperature characteristic at room temperature. One other crystal (crystal FA-67) showed an irregular temperature characteristic. The temperature run for this crystal was repeated several times and the same results were obtained each time. Most of the crystals showed smooth characteristics with the zero temperature coefficient points occurring at temperatures between 60° and 90°C.

The slope of the frequency-temperature curve was determined for each crystal at a temperature of 25°C (nominal laboratory temperature) to serve as figure of merit for the crystal. The data are shown in Table VI.

TABLE VI

TEMPERATURE COEFFICIENTS OF SEVERAL LABORATORY CRYSTALS

Crystal No.	Frequency (Mc/Sec)	Temperature Coeff. at 25°C Cycles/°C	PPM/°C
1A	220	-180	-0.82
2W	175	+30	+0.17
2W	275	+60	+0.21
3W	275	-300	-1.10
5	150	-69	-0.46
5	283	-133	-0.47
6	283	-160	-0.57
12	219	-190	-0.88
FA 40	195	-135	-0.69
FA 67	209	-175	-0.84
FA 89	217	-140	-0.65
FA 91	217	-162	-0.75
FA 105	231	-250	-1.08
FA 115	245	-155	-0.63
FA 117	245	-270	-1.10

4. High-Frequency Crystal-Controlled Oscillators

a. Introduction. The initial effort of the investigation of high-frequency oscillator circuits consisted of reviewing available literature, including reports on prior contracts. Existing vacuum-tube oscillator units, constructed on prior contracts, were again placed in operation. Previously, beat-frequency techniques had been used to confirm the presence of crystal-controlled oscillations. A recognizable audio tone from a heterodyne frequency meter indicated crystal control whereas the absence of such a tone and, particularly, the presence of a high noise level indicated a noncrystal-controlled oscillation having random frequency variations of several hundreds or thousands of cycles per second. A re-evaluation of this test method indicated that the presence of squegging could not generally be detected. When the frequency is counted on a Berkeley frequency meter system, any squegging becomes evident because of nonlinearities in the system.

When again placed in operation, many of the previously constructed vacuum-tube oscillators were found to squegg. The squegging rate was typically between 50 and 400 kc/sec. Similar difficulties were encountered with many of the recently constructed oscillators described in this report.

Many attempts were made to eliminate the squegging of the various vacuum-tube oscillators by conventional means. These attempts included changing the values of grid-coupling capacitors and grid return resistors, changing the plate and cathode by-pass and decoupling components, shifting the ground points and grounding methods, and changing components in the r-f circuits. Methods were not found to eliminate the squegging of some of the oscillators.

Changes in r-f circuitry were found to be more effective in reducing the squegging than changes in by-pass components. For example, with all of the oscillators except the capacitance-bridge oscillator, inductors were used in parallel with the crystals to provide antiresonance. This action is illustrated in Figure 77 where an uncompensated crystal response and a properly compensated response are shown. Any choice of compensating inductor which

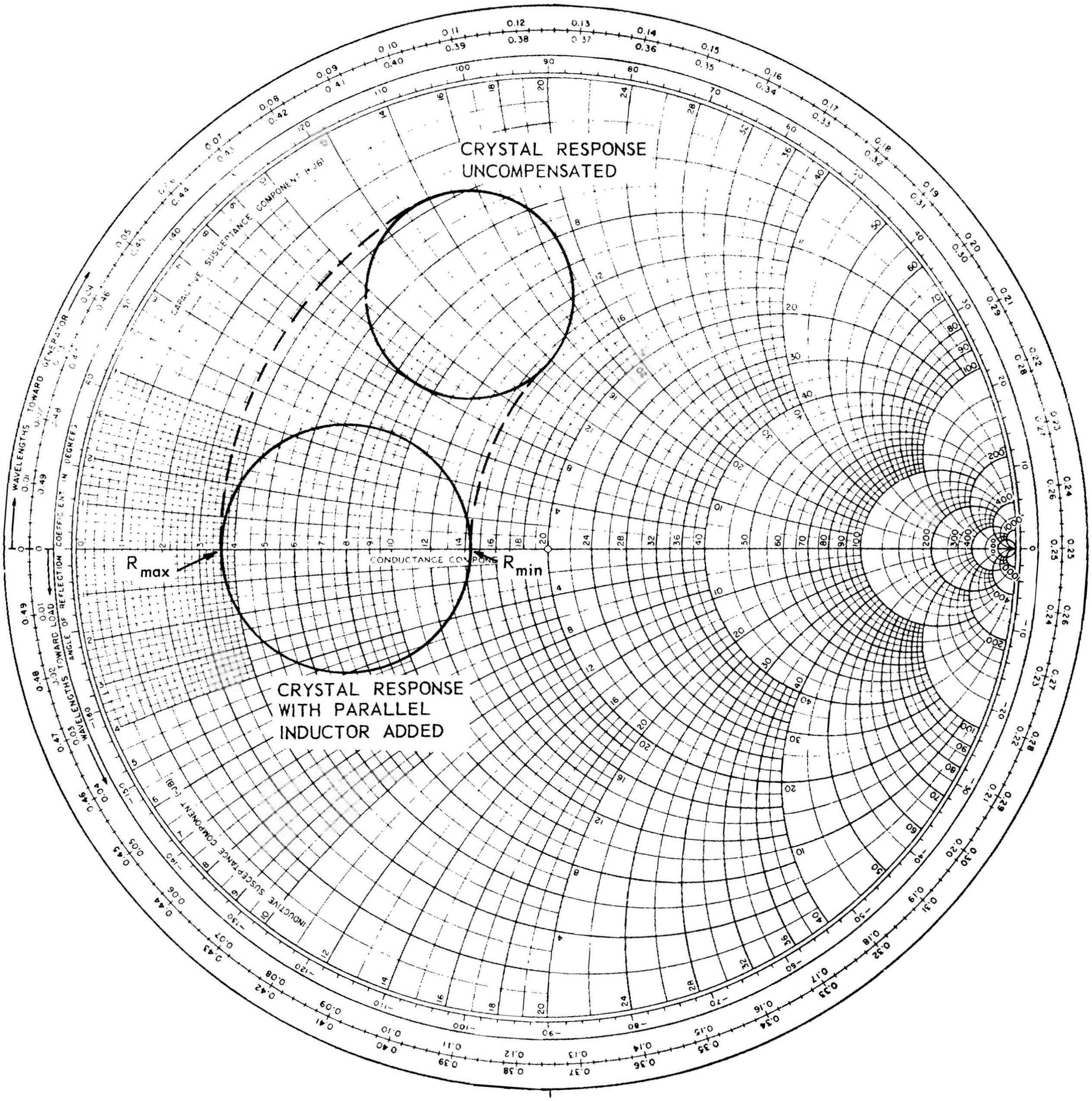


Figure 77.. Inductive Crystal Compensation.

placed the crystal response at positions other than approximately centered on the conductance axis generally produced squegging.

No other general difficulties were encountered in the construction of vacuum-tube oscillators; however, each oscillator showed various individualities which will be discussed later.

Each vacuum-tube oscillator was tested with a sufficient number of crystals to determine roughly the frequency range of operation and the required crystal quality. Figure 77 serves to define the terms R_{max} and R_{min} as used in the descriptions of the oscillators. The frequency of operation was generally near the frequency at which R_{min} occurred, as indicated by the substitution measurement system.

During the latter part of the contract period, three sample Texas Instruments transistors of the 2N1400 series were obtained for oscillator investigations. These transistors were reported to be capable of oscillation at frequencies as high as 500 mc/sec. One of the transistors was defective and another was damaged during the course of experiments.

Both free-running and crystal-controlled transistor oscillators were constructed. Crystal control was obtained at frequencies as high as 300 mc/sec. Typical frequency stabilities were an order of magnitude better than obtained with typical vacuum-tube oscillators. Frequency variations with both temperature and supply voltage were briefly investigated. Typical frequency variations with temperature followed very closely with the frequency variations of the crystal alone.

Some of the oscillators were also tested with a Philco Type 2N502 transistor. The results were very similar to that obtained with the Texas Instruments transistor.

b. Vacuum-Tube Crystal-Controlled Oscillators.

(1) The Cathode-Coupled Oscillator. The cathode-coupled oscillator circuit is a lower-frequency crystal-controlled oscillator circuit investigated and described by Armour.[†] A model of this oscillator was constructed to operate at 150 mc/sec by following the detailed steps outlined by Armour. Specifications of wire size, spacing, number of turns, and other details were closely followed. When the coils were checked on a Boonton Model 160A or Model 170A Q-Meter, the values agreed very closely with those specified. However, in the circuit, the required inductances differed widely. Because of differences in stray capacitances, the values of inductances had to be changed by as much as 50 percent to obtain proper operation. After following Armour's tune-up procedure, the oscillator was satisfactorily crystal controlled at 150 mc/sec. Output was obtained by loosely coupling a pickup coil to the plate inductance of one of the tubes. After amplification by two IFI Model 530 wide-band amplifiers, the output frequency was counted directly by the Berkeley frequency meter and converter. Because of nonlinearities (possibly in the wide-band amplifiers) some output was available at 300 mc/sec. A photograph of this oscillator is shown in Figure 78.

Armour does not give design procedures for the construction of oscillators for frequencies above 150 mc/sec. However, from the same basic circuit configuration with reduced lead lengths and inductances scaled from the 150 mc/sec unit, an oscillator which operated satisfactorily with crystal FA-89

[†]Gruen, H. E. and Plait, A. O., A Study of Crystal Oscillator Circuits. Final Report, Contract No. DA-36-039 SC-64609, Armour Research Foundation of Illinois Institute of Technology, Chicago, 14 August 1957.

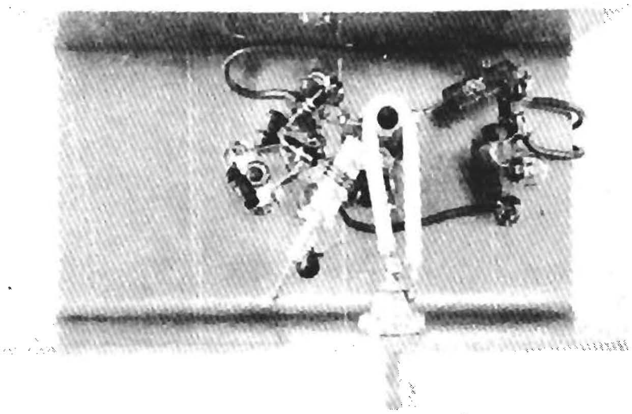


Figure 78. The 150-Mc/Sec Cathode-Coupled Oscillator.

at 217 mc/sec was constructed. A photograph of this oscillator is shown in Figure 79. The crystal was moved to the underneath side of the chassis to reduce the lead lengths and to reduce the heating from the vacuum tube. Instabilities due to heating of the crystal had been observed for the 150-mc/sec oscillator.

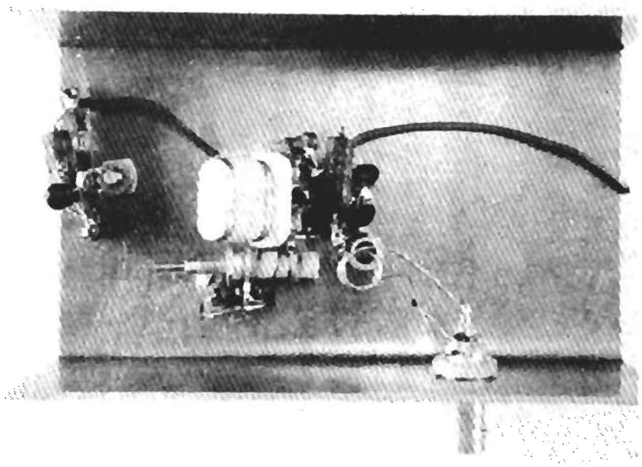


Figure 79. The 217-Mc/Sec Cathode-Coupled Oscillator.

The circuit configuration (same for both oscillators) is shown in Figure 80.

Both the 150- and 217-mc/sec oscillators maintained typical frequency

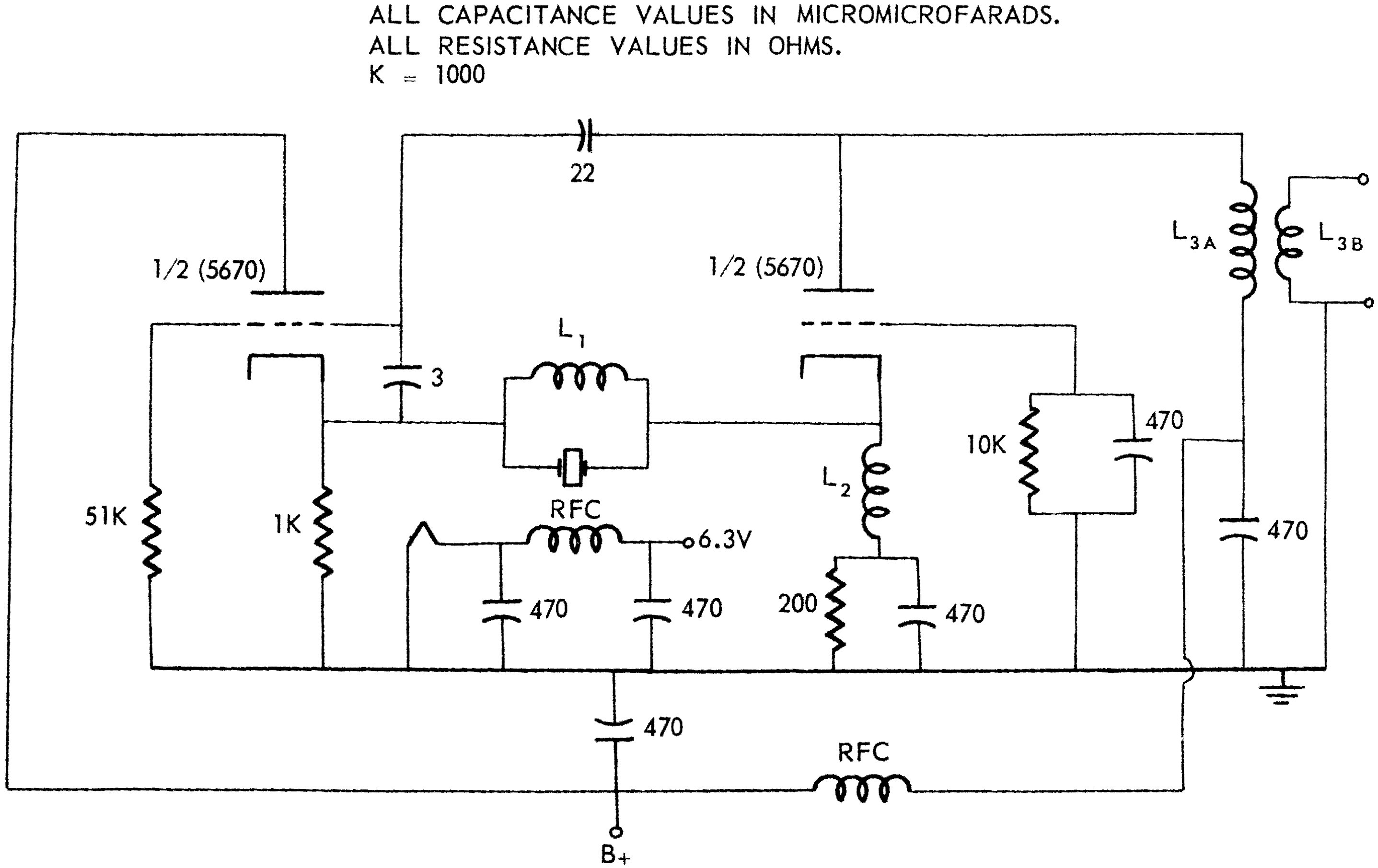


Figure 80. The Cathode-Coupled Oscillator Circuit Diagram.

instabilities of less than ± 10 cycles per second for periods of several seconds. Continuous recordings of frequency variations could not be made because of the lack of the necessary equipment. Likewise, facilities were not available for determining the effects of temperature changes.

(2) The Capacitance-Bridge Oscillator. A capacitance-bridge oscillator unit, originally described in Progress Report Nos. 1 and 2 of Contract No. DA-36-039 SC-71191, was again placed in operation. A photograph of this unit with minor component modifications made to improve the tuning characteristics is shown in Figure 81. The basic circuit diagram of the unit is shown in Figure 82.

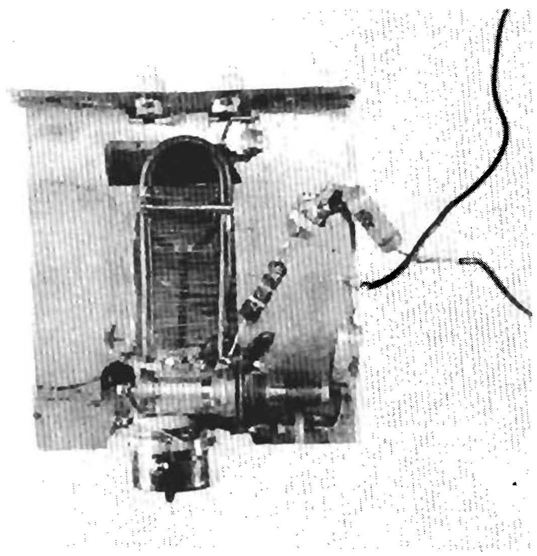


Figure 81. The 250-Mc/Sec Capacitance-Bridge Oscillator.

The oscillator is tuneable from 200 to 250 mc/sec and was operated with crystal FA-89 at 217 mc/sec.

Another variation of this oscillator was constructed to operate from 230 to above 300 mc/sec with a Mallory Inductuner as the chassis. One section of the Inductuner was used as the plate coil. The cathode coil was etched from a double-clad copper-laminated phenolic board with the cathode loop on one side and a Faraday shield on the other side. No provisions were made for tuning the

ALL CAPACITANCE VALUES IN MICROMICROFARADS.
ALL RESISTANCE VALUES IN OHMS.
K = 1000

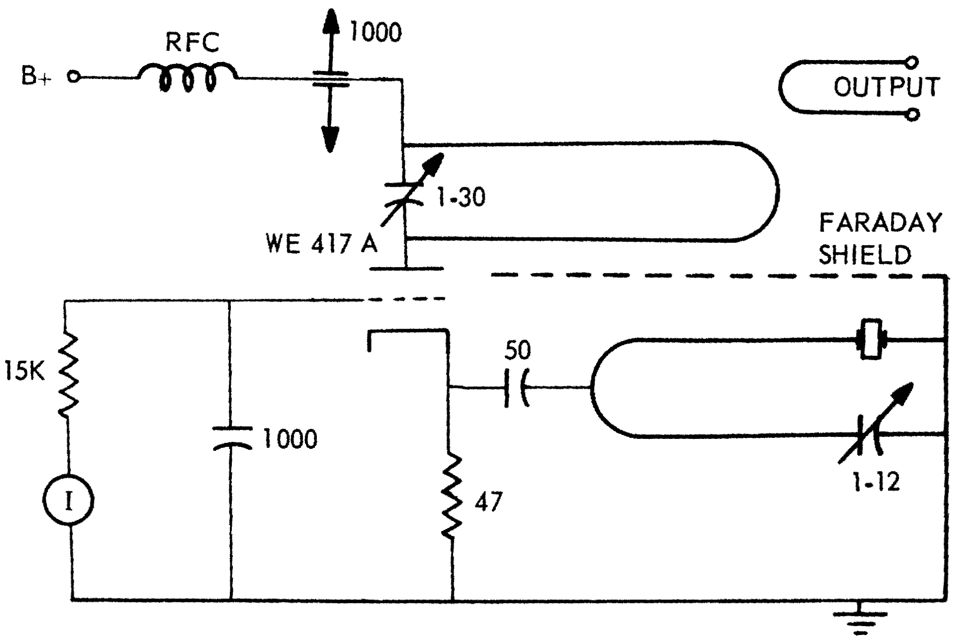


Figure 82. The Capacitance-Bridge Oscillator Circuit Diagram.

cathode coil. Oscillations were never obtained with this unit, possibly because of insufficient coupling between the plate and cathode coils.

Still another model of the capacitance-bridge oscillator was constructed entirely on a tube socket. This method of construction, which provided a minimum length of lead, is shown in Figure 83. Oscillations were obtained, but crystal control was not, probably because of the absence of a Faraday shield.

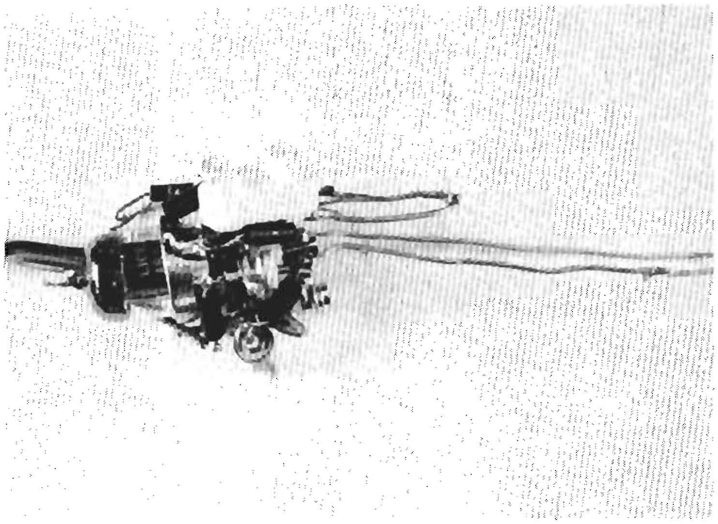


Figure 83. The Unitized Capacitance-Bridge Oscillator Circuit Diagram.

Squegging was again observed with some forms of the capacitance-bridge oscillator.

(3) The Plate-Degenerative Oscillator. Three plate-degenerative oscillator units were described in Progress Report Nos. 1 and 2 of Contract No. DA-36-039 SC-71191. The total frequency range covered by the units is 140 to 330 mc/sec (140 to 220 mc/sec for the first, 200 to 300 mc/sec for the second, and 260 to 330 mc/sec for the third). The circuit diagram is shown in Figure 84 and is the same for all units, except for minor changes. A photograph of the second unit is shown in Figure 85.

ALL CAPACITANCE VALUES IN MICROMICROFARADS.
ALL RESISTANCE VALUES IN OHMS.
K = 1000

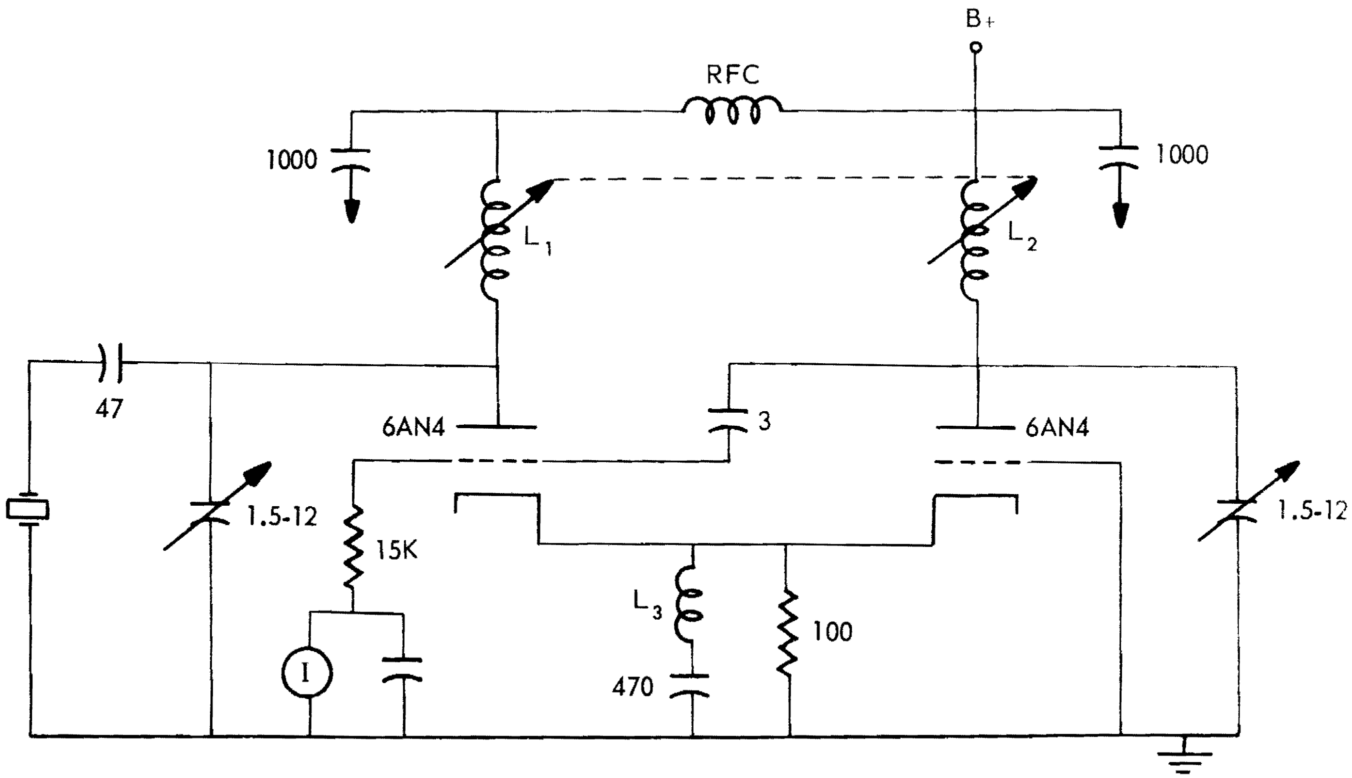


Figure 84. The Plate-Degenerative Oscillator Circuit Diagram.

Crystal FA-89 was used in both the first and second units to obtain crystal-controlled oscillations at 217 mc/sec. The tune-up procedure for obtaining crystal control with the plate-degenerative oscillator was less critical than

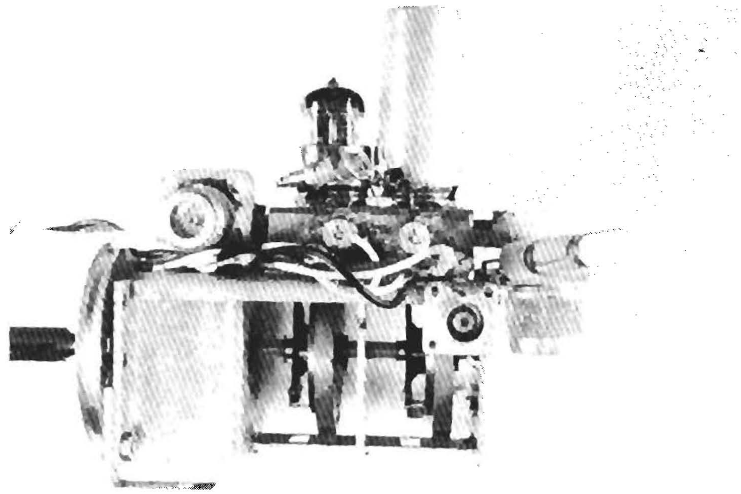


Figure 85. The 200- to 300-Mc/Sec Plate-Degenerative Oscillator.

for any of the other oscillators but at the same time the stability was poorer. Squegging was also observed with the highest frequency unit.

(4) The Grid-Degenerative Oscillator. The grid-degenerative oscillator is basically a grounded-grid oscillator with the grounding of the grid accomplished through a compensated crystal. The circuit diagram is shown in Figure 86. Over a moderate frequency range, the parallel resonant circuit consisting of the compensating inductance and the crystal capacitance produces a high-impedance antiresonance in the grid circuit to prevent oscillations. At crystal overtone response, the grid is grounded by the resonant resistance of the crystal to provide the necessary condition for oscillations.

A fixed-tuned model of this oscillator was designed to operate at 250 mc/sec. Typical crystal resistances at this frequency were, however, too

ALL CAPACITANCE VALUES IN MICROMICROFARADS.
ALL RESISTANCE VALUES IN OHMS.
K = 1000

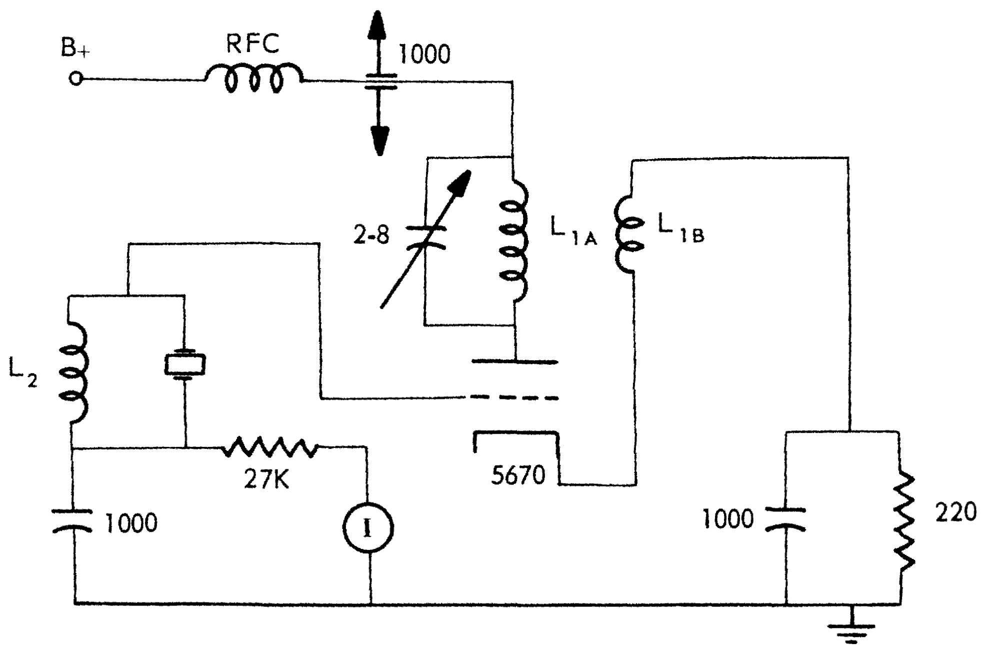


Figure 86. The Grid-Degenerative Oscillator Circuit Diagram.

high to permit oscillations to occur. Oscillations were readily obtained by replacing the crystal with a resistance or other low-impedance device. A photograph of a grid-degenerative oscillator is shown in Figure 87.

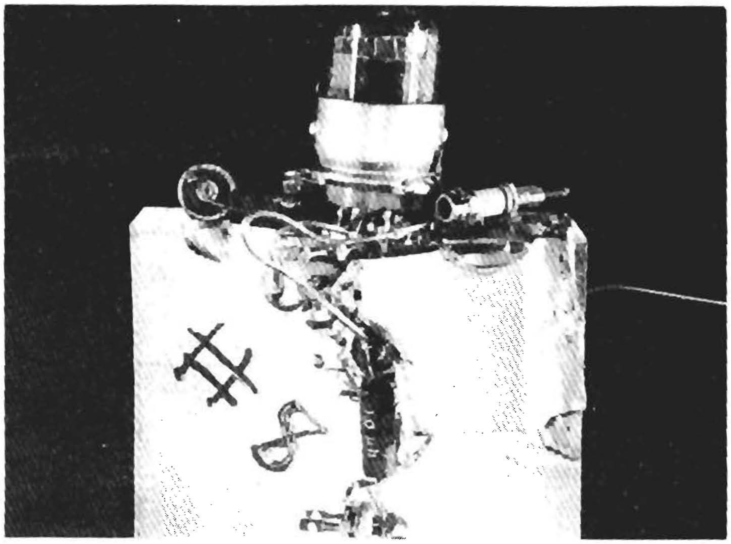


Figure 87. The 250-Mc/Sec Grid-Degenerative Oscillator.

(5) The Modified Grounded-Grid Oscillator. The modified grounded-grid oscillator is essentially a grounded-grid oscillator with the crystal in series with the cathode feed-back path. The circuit diagram is shown in Figure 88. A model of this oscillator, tuneable over the frequency range from 200 to 250 mc/sec, was constructed. When the oscillator was tested, squegging occurred over the entire tuning range. The squegging was eliminated between the frequencies of 210 and 220 mc/sec by carefully positioning the cathode coil with respect to the plate coil. Crystals FA-89 and 6 both provided crystal control at 217 mc/sec. Crystal 12 provided control at 219 mc/sec. The stability of this oscillator was comparable to that of the cathode-coupled oscillator at 217 mc/sec. A photograph of this oscillator unit is

ALL CAPACITANCE VALUES IN MICROMICROFARADS.
ALL RESISTANCE VALUES IN OHMS.
K = 1000

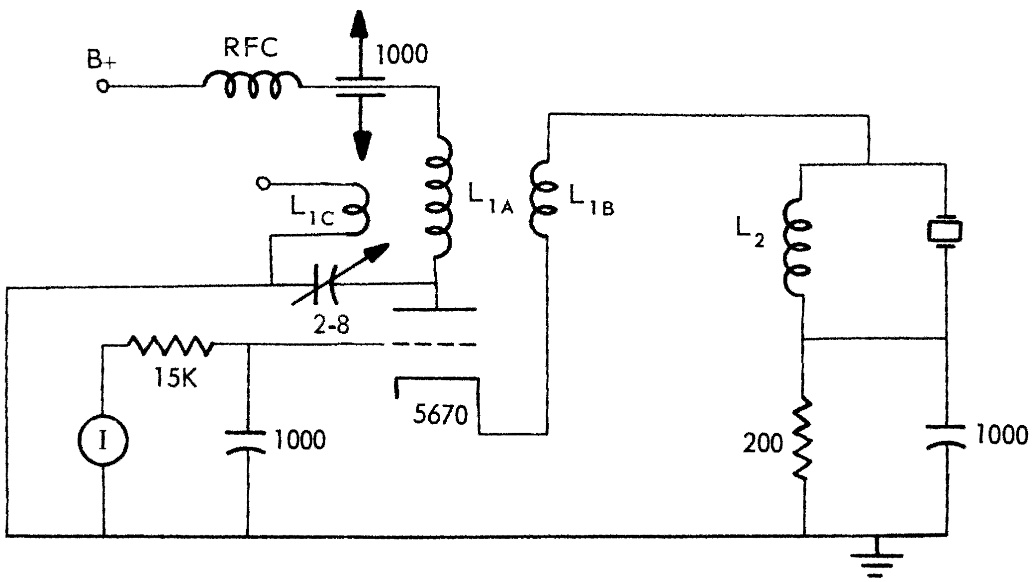


Figure 88. The Modified Grounded-Grid Oscillator Circuit Diagram.

shown in Figure 89.

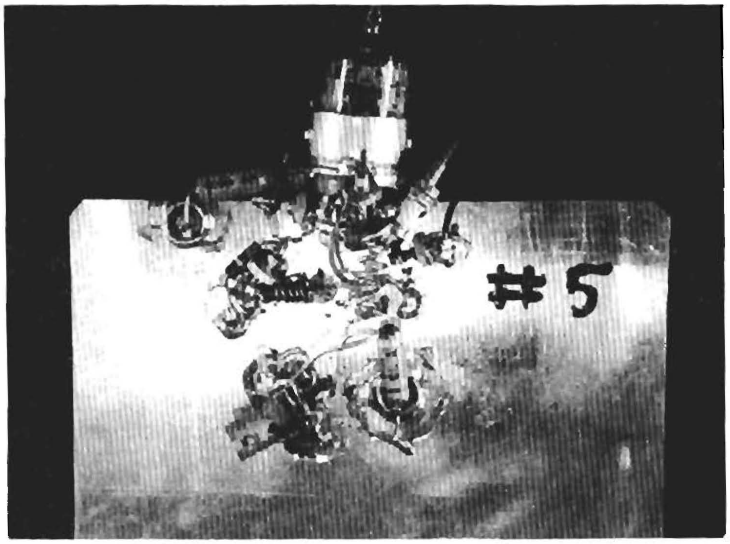


Figure 89. The 200- to 300-Mc/Sec Modified Grounded-Grid Oscillator.

(6) The Cathode-Degenerative Oscillator. The cathode-degenerative oscillator is a tuned-plate tuned-grid oscillator with the cathode returned through a compensated crystal. The circuit diagram is shown in Figure 90. Except at crystal overtone frequencies, the cathode impedance is sufficiently high to prevent oscillations from occurring. With the triode vacuum tube, the plate-to-grid capacitance is sufficient to maintain oscillations, even with relatively high impedances in the cathode circuit. No coupling between the plate and grid inductances is required.

A model of this oscillator was constructed on the frame of a Mallory Inductuner with two of the Inductuner sections serving as plate- and grid-circuit elements. A photograph of the oscillator is shown in Figure 91. The crystal was compensated in the usual manner by placing an inductance across the crystal socket.

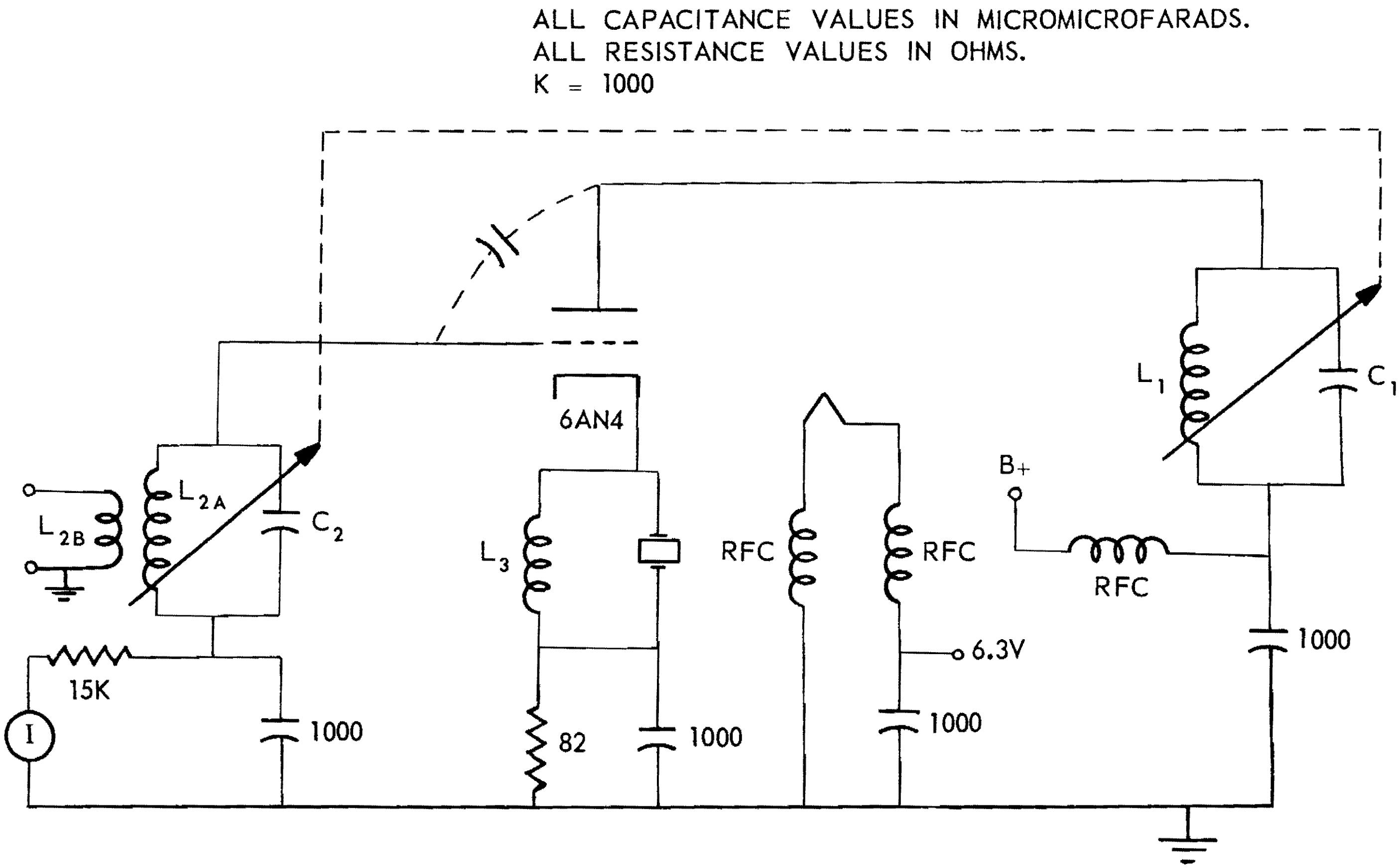


Figure 90. The Cathode-Degenerative Oscillator Circuit Diagram.

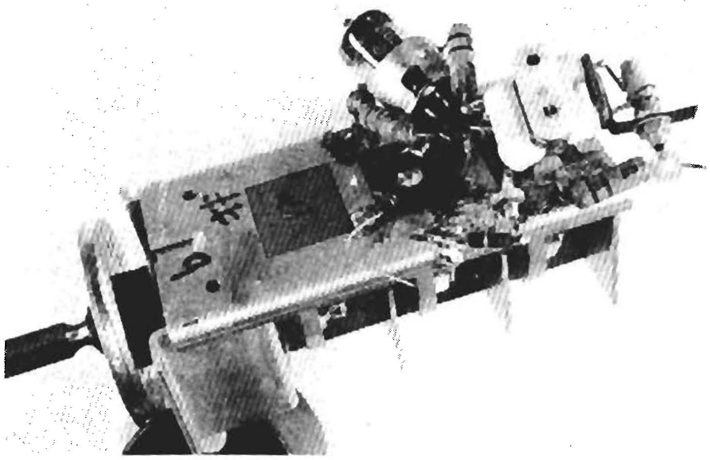


Figure 91. The 200- and 300-Mc/Sec Cathode-Degenerative Oscillator.

The first model of this oscillator to be constructed oscillated at 250 mc/sec with crystal 6 and with a stability which appeared to be better than that of any of the other oscillators described for the frequency range above 200 mc/sec. Oscillation over a wide range of frequencies was possible when the crystal socket was replaced by a Y-yoke crystal socket so that both the crystal and the compensating inductor could be chosen. With this arrangement, crystal-controlled oscillations were obtained from 200 to 250 mc/sec. Crystal control at higher frequencies was not obtained because of the excessive lengths of leads to the Y-yoke socket.

Squegging was observed with this oscillator on several occasions. A suitable choice of crystal compensating inductor eliminated the squegging in every case. By trial and error, the correct inductors were chosen for several individual crystals. Table VII shows the minimum and maximum resistance values of several crystals which provided crystal control.

The typical oscillator instability with the crystals of Table VII was ±10 cycles per second for a period of 30 seconds. Supply voltage variations of 10 percent produced frequency variations from 500 to 2000 cycles per second.

A second model of the cathode-degenerative oscillator was constructed to obtain crystal control at higher frequencies. Particular care was given to the cathode circuitry to maintain minimum lead lengths. Provisions were made for soldering the crystal compensation inductor into the circuit. A conventional crystal socket was used, however, for mounting the crystal.

TABLE VII

CRYSTALS FOR USE WITH THE FIRST CATHODE-DEGENERATIVE OSCILLATOR

Crystal No.	Frequency (Mc/Sec)	R_{min} (Ohms)	R_{max} (Ohms)
6	250	110	500
5	250	130	600
FA-117	245	50	600
MA-23	242	180	650
FA-105	231	55	500
FA-89	217	59	1000

With this oscillator, crystal control was obtained at frequencies as high as 290 mc/sec with stabilities comparable to those previously obtained. Table VIII lists the characteristics of the crystals used with this oscillator.

The oscillator frequency, with crystal 2W, changed less than ±10 cycles per second for one period of 8 minutes. A 10-percent supply voltage change, with crystal 2W, produced an 1800-cycles-per-second frequency change. The

TABLE VIII

CRYSTALS FOR USE WITH THE SECOND CATHODE-DEGENERATIVE OSCILLATOR

Crystal No.	Frequency (Mc/Sec)	R_{min} (Ohms)	R_{max} (Ohms)
2W	275	68	500
5	283	104	400
6	283	82	360
FA-117	245	50	600
FA-40	252	110	300
FA-89	279	50	250

approximate temperature coefficient of this oscillator and crystal combination was 250 cycles per second per degree centigrade.

The second cathode-degenerative oscillator was also operated at lower frequencies. One crystal compensation inductor provided crystal control with all of the crystals listed in Table IX. Typical short-term instabilities were again ±10 cycles per second, even with the poorer crystals such as MA-38 and MA-39. A particular advantage of this oscillator unit was its ability to maintain crystal control with almost any crystal having a response between 200 and 290 mc/sec.

A third model of the cathode-degenerative oscillator was constructed to operate at lower frequencies for comparison with the higher frequency units. A Mallory Inductuner was again used for the plate- and grid-tuned circuits. The construction was similar to the higher frequency units. Crystal 12 was operated in this unit at a frequency near 100 mc/sec with an instability of approximately ±10 cycles per second for a period of 3 minutes. Plate supply voltage variations of 10 percent produced frequency variations of 200 cycles per second. Table X lists some of the crystals which provided crystal control

TABLE IX

MEDIUM-FREQUENCY CRYSTALS FOR USE WITH THE SECOND CATHODE-DEGENERATIVE OSCILLATOR

Crystal No.	Frequency (Mc/Sec)	R_{min} (Ohms)	R_{max} (Ohms)
FA-59	202	59	550
FA-67	209	112	670
FA-89	217	59	1000
FA-105	230	55	500
2W	225	62	1000
3W	225	†	†
1-A	220	†	†
2-A	220	†	†
MA-39	217	#	#
MA-38	217	#	#

†Crystal resistance data have not yet been obtained with these crystals.

#These crystals had been disregarded during previous crystal measurement runs because of their very poor quality. The minimum resistance was so high (probably much greater than 500 ohms) that neither the Crystal Measurements Standard System nor the substitution system could provide data.

TABLE X

LOW-FREQUENCY CRYSTALS FOR USE WITH THE THIRD CATHODE-DEGENERATIVE OSCILLATOR

Crystal No.	Frequency (Mc/Sec)	Crystal (Number)	Frequency (Mc/Sec)
12	59.990090	FA-57	145.993250
12	99.996634	FA-92	154.913500
12	139.990500	3W	175.701610
12	180.982620	FA-92	217.965380
		3W	224.604500

with this unit.

c. Transistorized Crystal-Controlled Oscillators

(1) The Base-Degenerative Oscillator. The first transistorized oscillator to be constructed was the grounded-base free-running oscillator shown in Figure 92. Oscillations were obtained at frequencies from 160 to 230

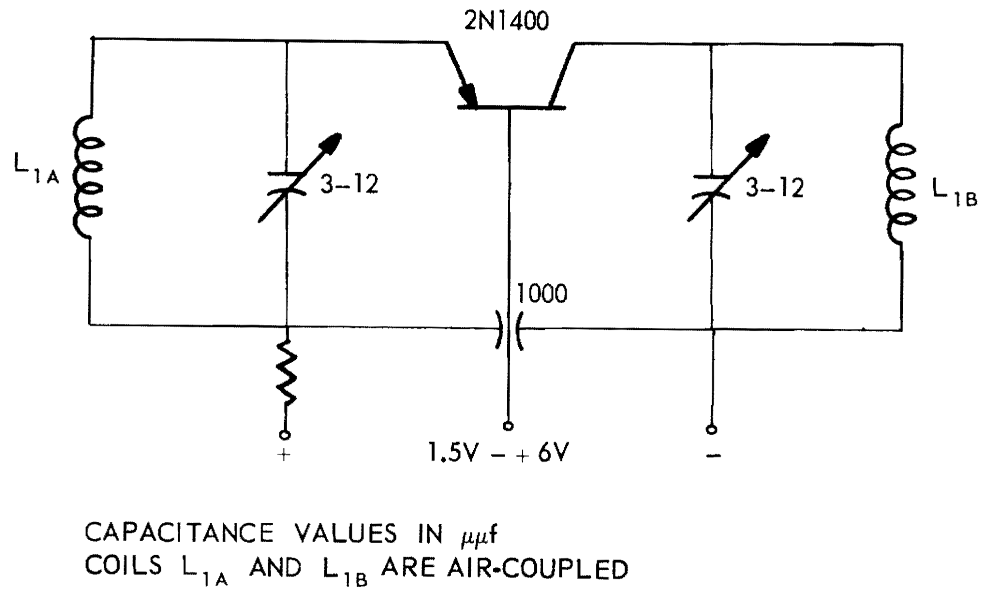
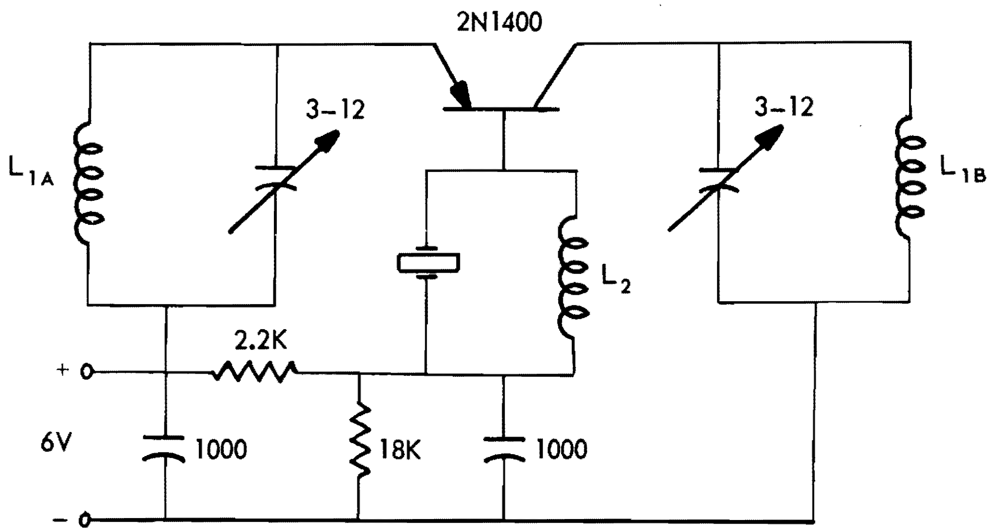


Figure 92. The Tuned-Collector Feedback Oscillator.

mc/sec. The basic configuration is made suitable for crystal control by inserting the crystal into the base circuit. At all frequencies except the crystal overtone responses, the crystal unit impedance should be sufficiently high to prevent oscillations through base circuit degeneration.

The oscillator was converted to crystal control as suggested above. Some modifications of the biasing circuit, as shown in Figure 93, were required.



CAPACITANCE VALUES IN $\mu\mu$f.
RESISTANCE IN OHMS, K = 1000
COILS L_{1A} AND L_{1B} ARE AIR-COUPLED

Figure 93. The Base-Degenerative Oscillator Circuit Diagram.

A photograph of the oscillator is shown in Figure 94. After a suitable compensation inductor was chosen, crystal FA-89 provided crystal control at 217 mc/sec. With the proper compensation inductor, oscillations could not be obtained at frequencies other than the crystal overtone response. No temperature control of the circuit or shielding of the circuit was employed. Figure 95 shows the frequency variations of the oscillator for a period of 44 minutes. Air movement in the laboratory was kept to a minimum to reduce the short-term frequency variations. Figure 96 shows the frequency variations over a period of 3 hours. These frequency changes were due almost entirely to changes

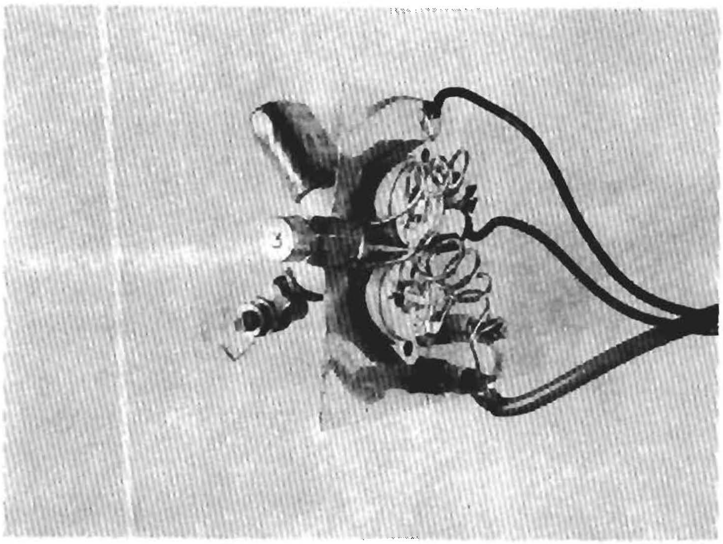


Figure 94. Photograph of the Base-Degenerative Oscillator.

in temperature of the crystal. (The room temperature near the oscillator unit was also observed.)

The frequency of this oscillator was recorded as 216.949014 mc/sec at a room temperature of 29.1°C. After 10 hours of operation the frequency had changed to 216.949436 mc/sec while the temperature had changed to 25.0°C. This represented a frequency change of approximately -100 cycles per second per degree Centigrade compared to the crystal coefficient of -140 cycles per second per degree Centigrade.

Crystal 2W was also operated in this unit because of its positive frequency-temperature coefficient. This time, the circuit was wrapped in glass wool and placed in a shield box. Frequency shifts due to short-term temperature variations as well as due to capacitance effects were thus reduced.

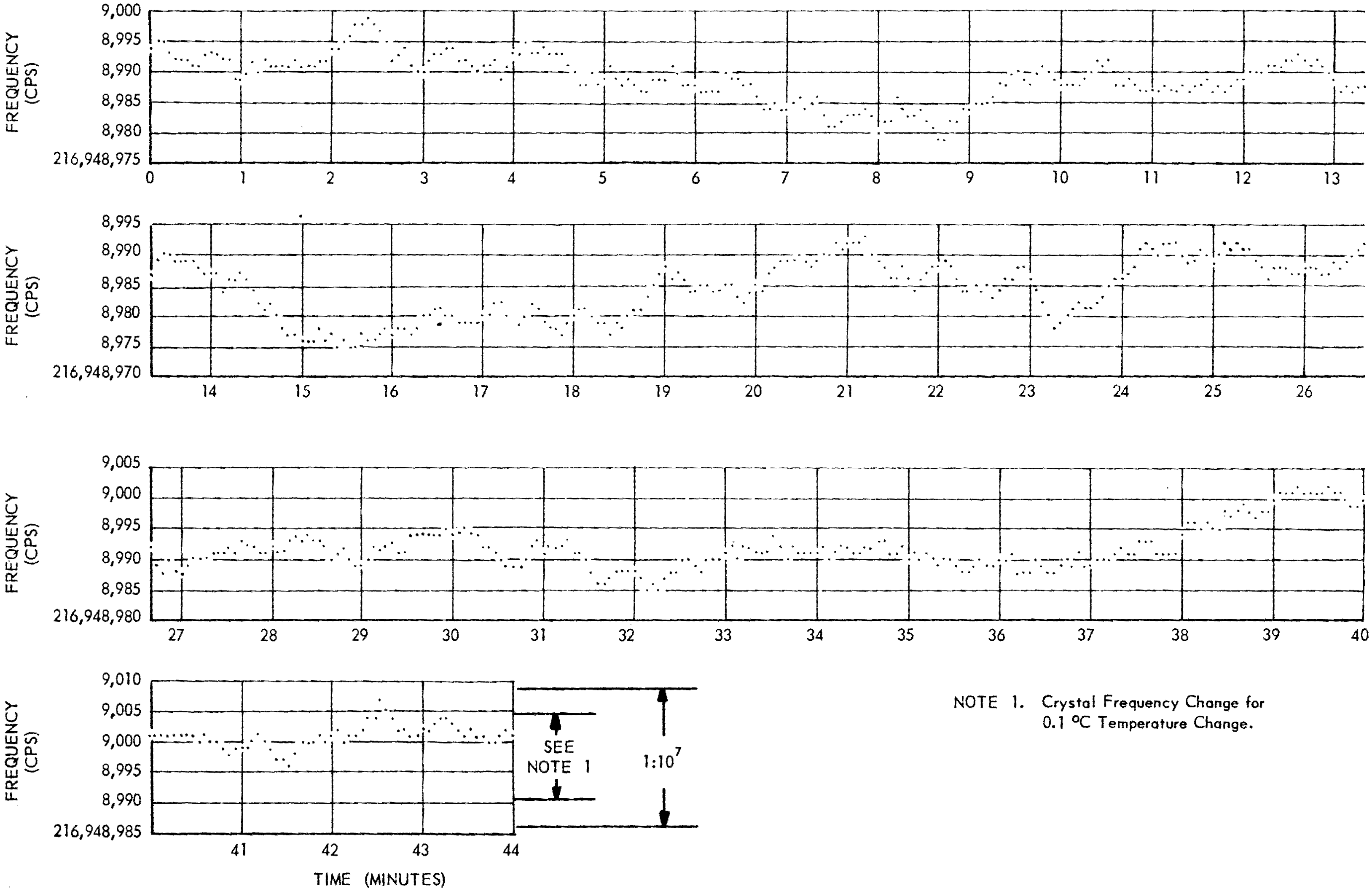


Figure 95. Frequency Variations of the Base-Degenerative Oscillator for a Period of 44 Minutes.

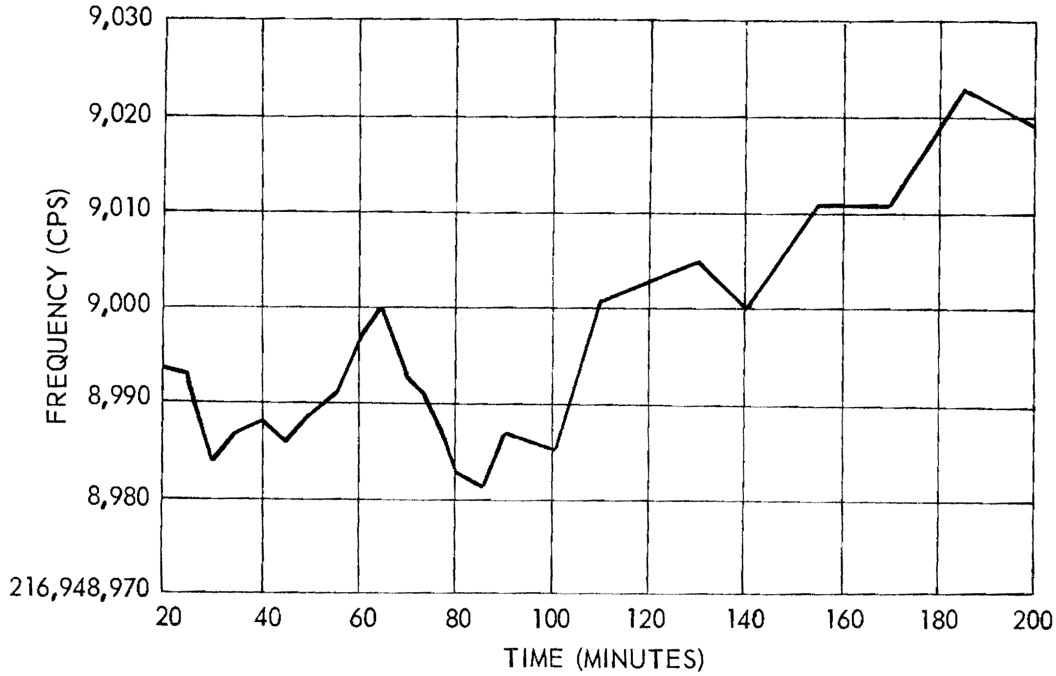


Figure 96. Frequency Variations of the Base-Degenerative Oscillator for a Period of 3 Hours.

Frequency variations due to slow temperature changes were not reduced since temperature regulation was not employed. Figure 97 shows the frequency variations of the oscillator at a nominal frequency of 175 mc/sec. The upper part of the figure shows the frequency variations immediately after the circuit was energized while the lower portion of the figure shows frequency variations 4 hours later. After the 4 hours of warm-up, the maximum frequency variations were ± 2 cycles per second for a period of 10 minutes. The distribution of points indicated that the variations were not greater than ± 1 cycle per second. (The resolution of the frequency measurement equipment is ± 1 cycle per second.) During the 4-hour warm-up period, the laboratory ambient temperature changed from 25.0° to 29.0°C. The frequency change was +27 cycles

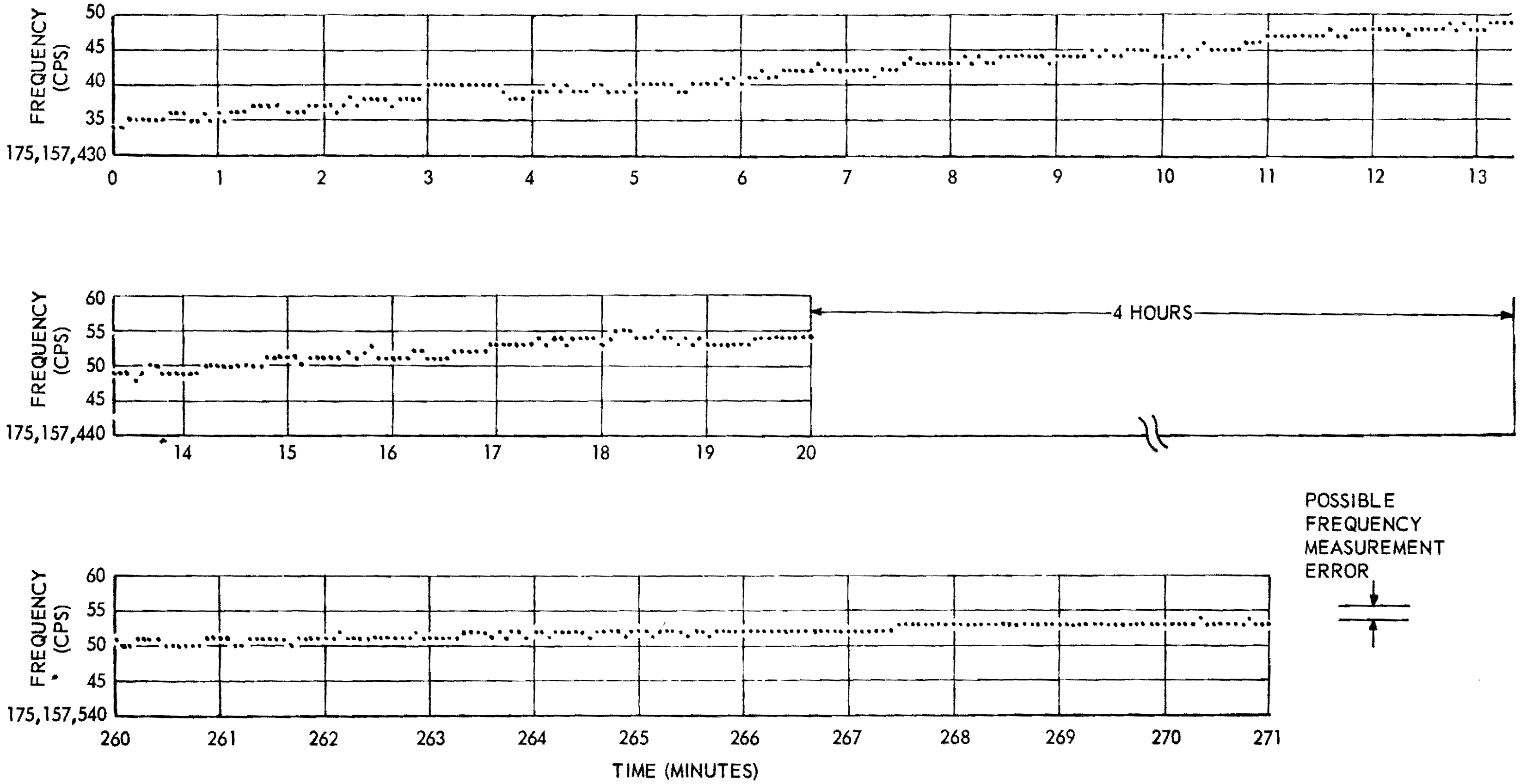


Figure 97. Frequency Variations of the Base-Degenerative Oscillator in an Insulated Shield Box.

per second per degree centigrade compared to +30 cycles per second per degree centigrade for the crystal alone.

The entire circuit was then placed in a crude oven in an attempt to improve the long-term stability. The temperature within the oven, however, was found to change by more than one degree centigrade as the thermostat cycled. These variations were partially smoothed by the insulation around the circuit. A photograph of the oscillator, insulating box, and oven is shown in Figure 98.

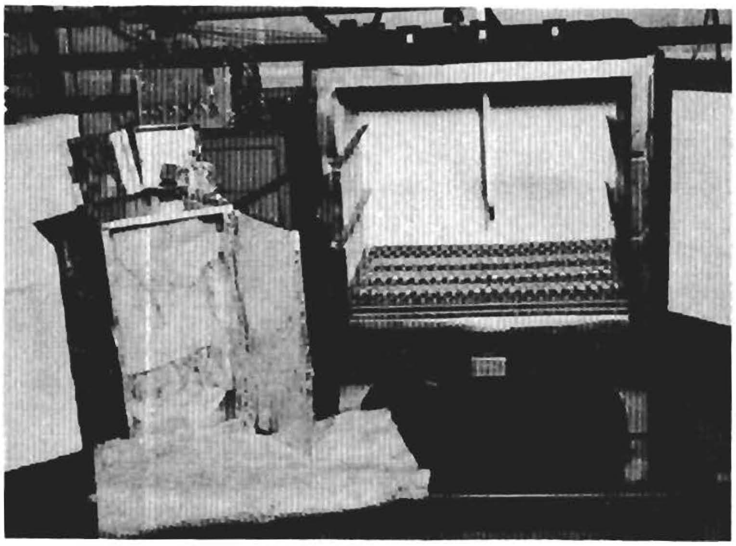


Figure 98. A Transistorized Oscillator, Shield Box, Insulating Box, and Oven.

The resulting frequency variations are shown in Figure 99. Also shown are the on and off periods of the oven. The irregularity of the oven cycling indicated very poor temperature control since the ambient temperature was relatively constant during this period of time. A Hewlett-Packard Model 524C frequency meter was borrowed to obtain the frequency data so that a resolution of 0.1 cycle per second could be obtained.

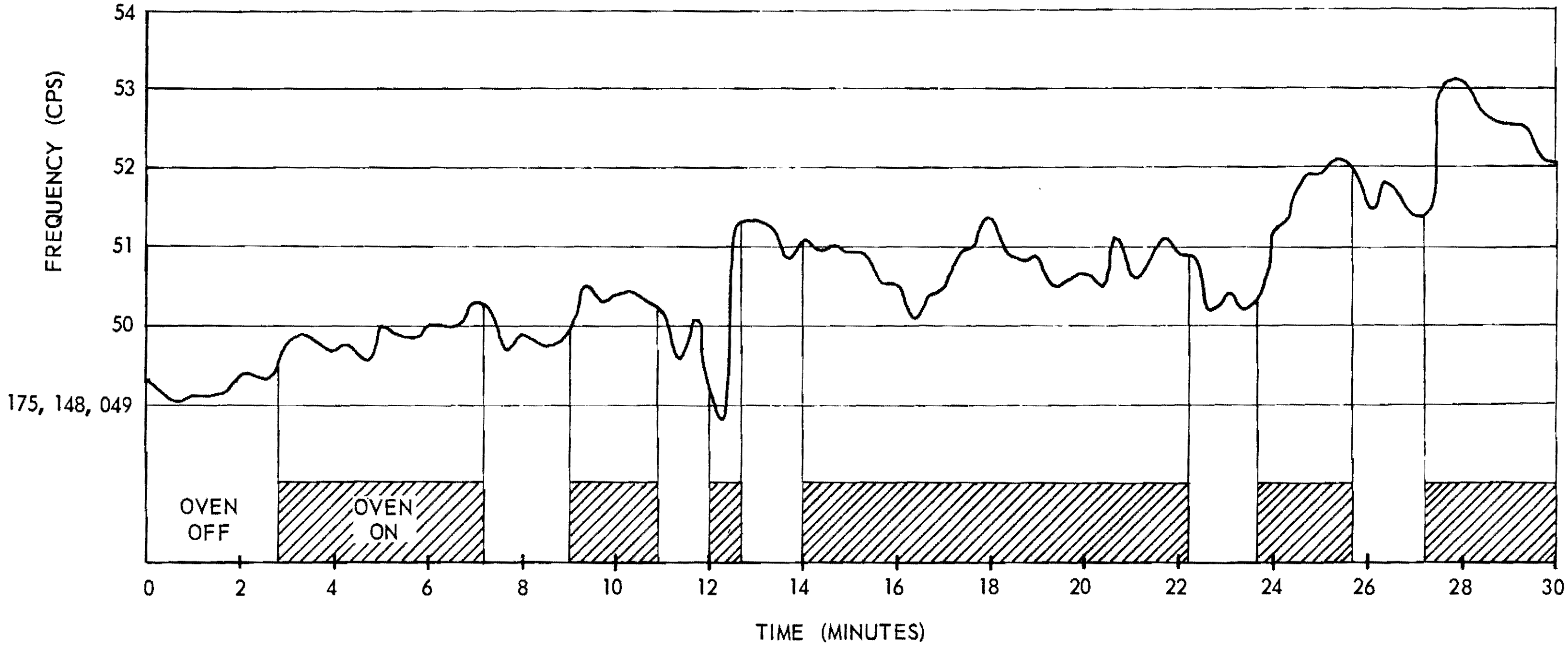


Figure 99. Frequency Variations of the Base-Degenerative Oscillator in an Oven.

The total frequency change during the half-hour period shown in Figure 99 was 4 cycles per second. With crystal 2W, a temperature change of only 0.1°C will produce a frequency change of 3 cycles per second. A more precise oven is thus required in order to obtain useful data.

A nickel-cadmium storage battery (6 volts) was used as the power source for the above oscillator unit so that frequency variations would not result from voltage changes. By adding an additional cell, the supply voltage was changed from 6.2 to 7.5 volts. The resulting frequency change was 2000 cycles per second or approximately 0.5 ppm per one percent voltage change.

This same oscillator unit was operated with a Philco Type 2N502 transistor and crystal 3W. The stability was approximately the same as indicated above.

With this circuit, the frequency of oscillation could be changed by as much as 6000 cycles per second without impairing the frequency stability. This fact indicated that the phase stability of the transistor and associated circuitry was very good.

A second model of this oscillator was constructed so that it could be enclosed in a shield box 2-1/2 inches cube. The frequency was adjusted to 225 mc/sec with crystal 2W and transistor type 2N502. The instability was less than ±1 cycle per second for periods of 6 minutes or longer.

A third model of this oscillator was constructed to operate at 296 and 300 mc/sec with transistor type 2N502. The short-term stability was somewhat poorer, partially as a result of the poorer crystals available at this frequency. Precise stability data have not been obtained for this oscillator.

(2) The Transistorized Hartley Oscillator. Several other oscillator configurations were investigated in an attempt to reduce the number of tuned circuits required for crystal-controlled oscillations. One such oscillator is the Hartley configuration shown in Figure 100. With this circuit, however, the crystal inductive compensation was very critical. This

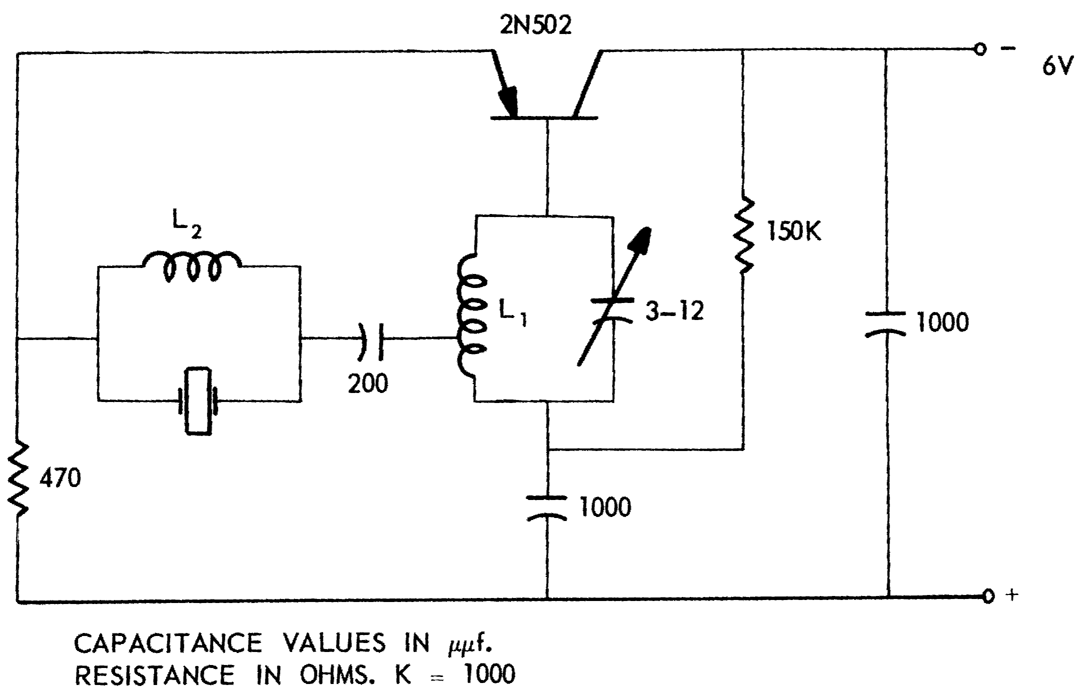


Figure 100. The Transistorized Hartley Oscillator Circuit Diagram.

circuit was actually more difficult to tune than was the base-degenerative oscillator. Crystal-controlled oscillations were obtained at 145 mc/sec with crystal FA-40. The output voltage was very small and the stability was only moderately good. A photograph of the oscillator is shown in Figure 101.

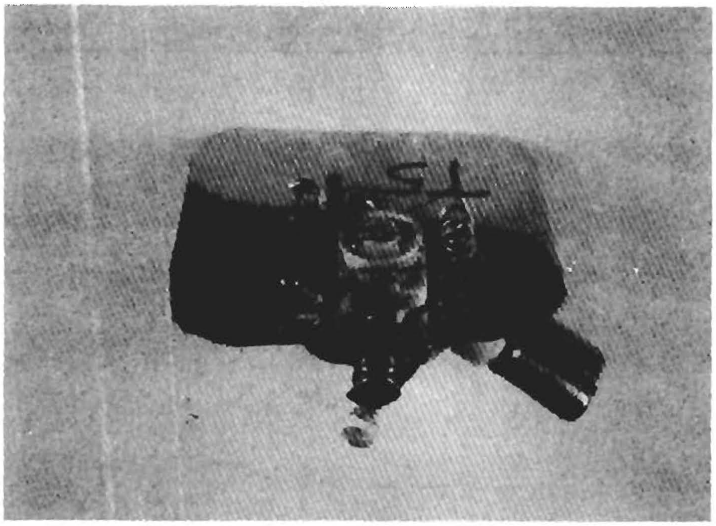
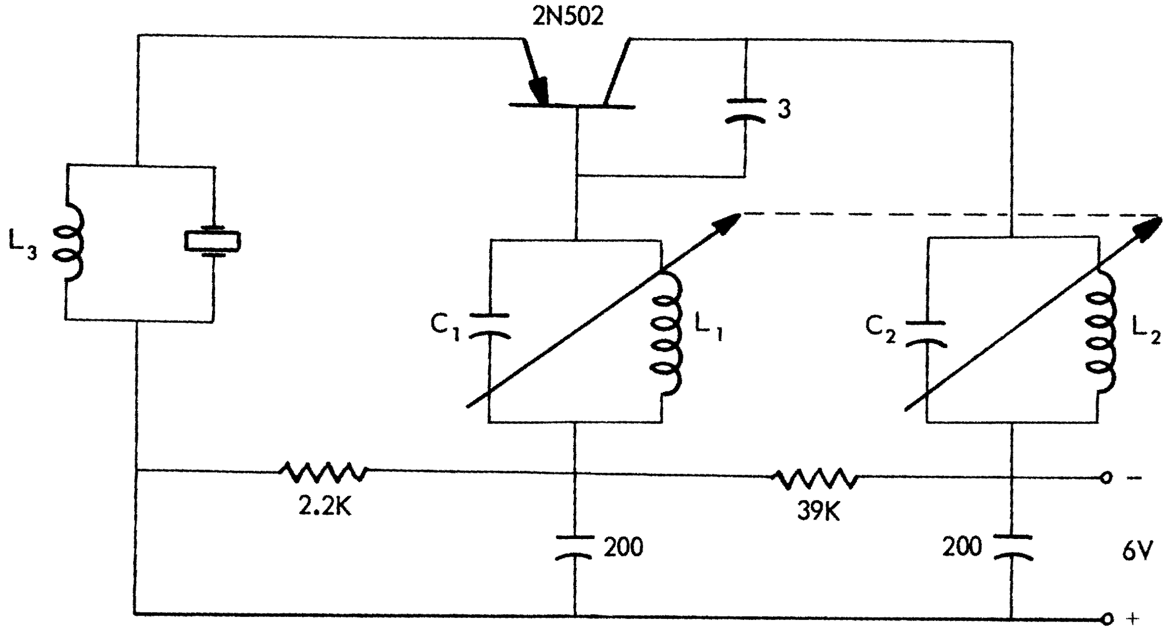


Figure 101. Photograph of the Transistorized Hartley Oscillator.

(3) The Emitter-Degenerative Oscillator. A transistorized version of the cathode-degenerative oscillator was constructed since the vacuum-tube model of this configuration showed excellent characteristics. The circuit of the transistorized oscillator is shown in Figure 102. A UHF Mallory Inductuner was used in the construction as shown in Figure 103. Crystal 12 was operated at 140 mc/sec with an instability of less than one cycle per second for periods of several minutes. The observation was also made that the supply voltage could be removed for a minute or more and then replaced with a frequency disturbance lasting less than 10 seconds after the return of the supply voltage.

The tuning range of this oscillator was, however, limited to frequencies below 150 mc/sec by the minimum inductance of the Inductuner and the relatively large capacitance of the transistor. An Inductuner having a lower



CAPACITANCE VALUES IN $\mu\mu$f.
RESISTANCE IN OHMS. K = 1000.
L_1 AND L_2 ARE SECTIONS OF A MALLORY INDUCTUNER.

Figure 102. The Emitter-Degenerative Oscillator Circuit Diagram.

impedance and a lower minimum inductance appears to be necessary for high-frequency operation with transistors.

d. Summary of Oscillator Data. The types of measurement which could be made on the previously described oscillators were severely limited by the available facilities. All frequency measurements were made by visual observation of a Berkeley frequency meter. A more desirable frequency measurement procedure would have required an analog frequency-voltage converter and a recording voltmeter. Such equipment would have provided a more accurate

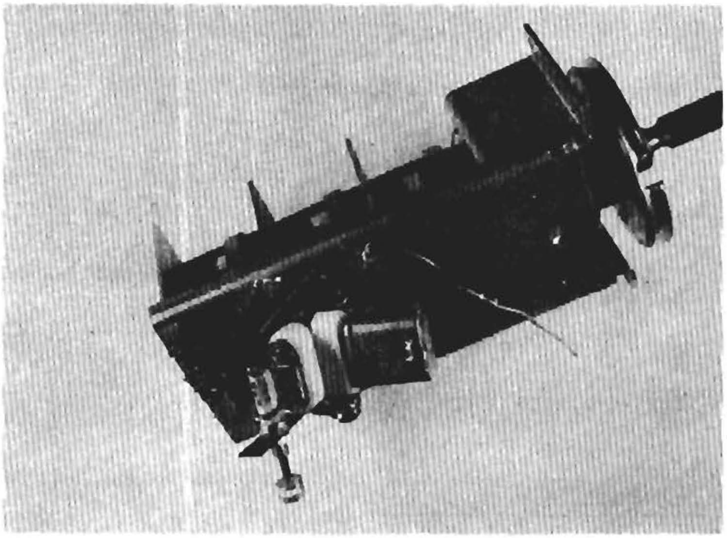


Figure 103. Photograph of the Emitter-Degenerative Oscillator.

record of frequency variations with imposed conditions.

Only very crude temperature control was possible (no temperature control was attempted with the vacuum-tube oscillators). Thus, adequate frequency-temperature data could not be obtained. After crystal frequency-temperature data were obtained, much of the observed oscillator frequency change could be attributed to the crystal characteristics alone.

Provisions for measuring crystal power dissipation have not yet been completed. A probe was constructed several months ago; however, the manufacturer of a special connector for connecting the probe to an indicating instrument has not has not yet been able to supply the connector.

After various measurement facilities are completed, additional data on both the vacuum-tube and transistorized oscillators can be obtained. Certain conclusions are, however, tentatively possible. These are: (1) the frequency stability of transistorized oscillators is generally much better than that of vacuum-tube oscillators, (2) comparable power output can be obtained from transistorized units with source powers of about 2 percent of that required for vacuum-tube oscillators, and (3) fewer circuit elements are generally required with transistorized oscillators due to the lack of filament decoupling networks. In addition, a frequency-temperature stability with transistorized oscillators comparable to that of the crystal alone appears to be readily possible. Recording equipment and more precise frequency measurement equipment will be required before more accurate data can be obtained.

C. Phase III. Aging of Quartz Resonators

1. Introduction

This phase of the work, assigned the Project No. A-402-13 by the Engineering Experiment Station of Georgia Institute of Technology, was initiated on 1 March 1959 and was a continuation of the work prior to that date under Contract No. DA-36-039 SC-78910, Georgia Tech Project No. A-402-3. The work undertaken on 1 March under Contract No. DA-36-039 SC-78905, was subsequently expanded under modification No. 1 to the Contract and renewed for an additional period of 12 months starting 1 July 1959, under Modification No. 4.

Investigation of the aging of 16.25-mc AT-cut quartz resonators procured from industrial sources and stored at 25°, 85°, and 125°C was completed; studies of similar units fabricated here in glass containers were continued.

The task of setting up a frequency-measuring system for quartz resonators of 100-mc/sec frequency has been completed. The ovens for storage of units at 0°, 60°C and for cycling between those temperatures were partially completed. Resonator blanks for 100-mc/sec operation were obtained, but only one group of resonators was fabricated.

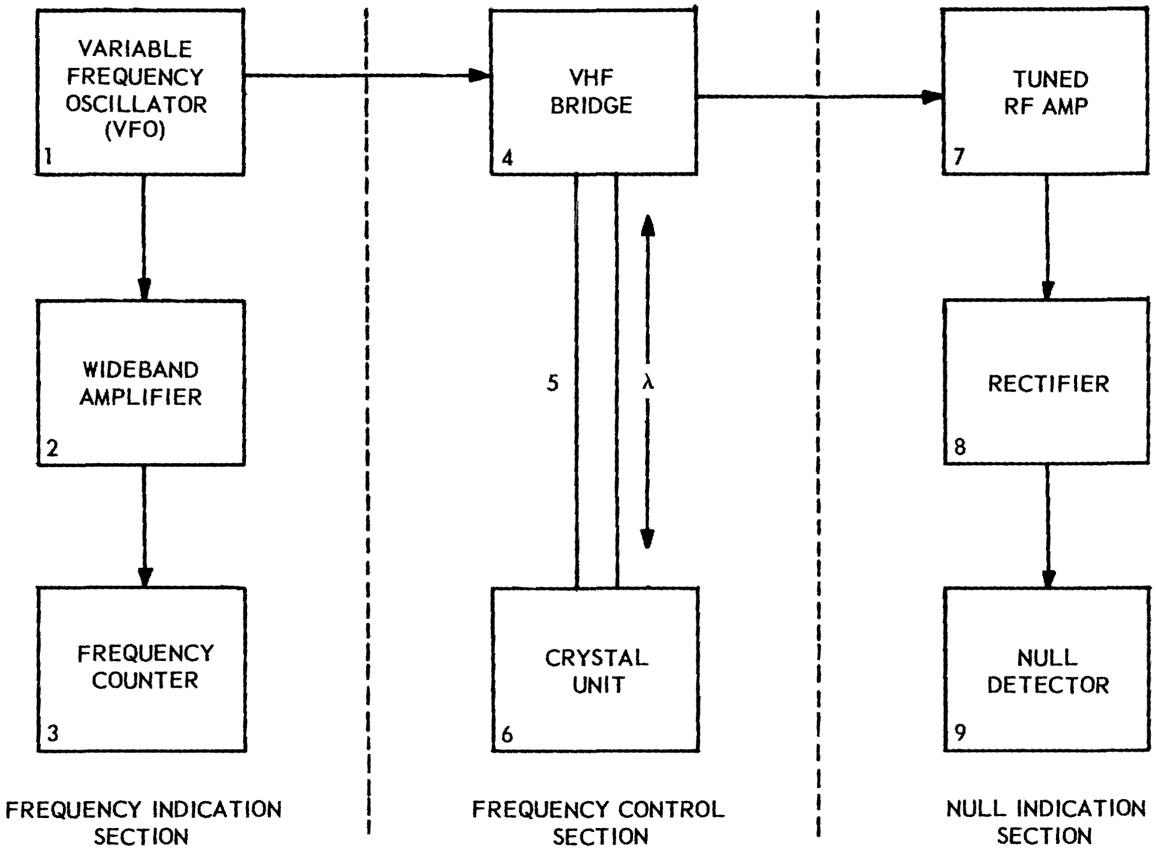
2. Apparatus

a. Frequency-Measuring System for 100-Mc/Sec Resonators. The measurement of the frequencies of a number of 100-mc/sec resonators daily, with a precision of ± 2 parts in 10^8, required the design and construction of a frequency-measuring system of the specified accuracy and a reasonable speed in making measurements. Likewise, ovens for accurate temperature control of resonators stored at specific temperatures of 0° and 60°C and cycling between these temperatures were necessary.

The frequency-measuring system consisted of an oscillator, the CI Meter TS-15 (or equivalent) for driving the crystal, a VHF bridge and associated instruments for adjusting the crystal to series resonance; these included a null detector, an amplifier, and a frequency counter. A block diagram of the system is shown in Figure 104 and the laboratory setup in Figure 105. The VHF bridge and the rectifier (Item 8 of Figure 104) were constructed here. For connection to resonators in ovens, a tuned coaxial line to the resonators was required.

(1) The VHF Bridge. The frequency control section (consisting of the VHF bridge, the resonant twin-coaxial transmission line, and the crystal) is the heart of the frequency-measuring system. The other sections utilize or display information derived from this section.

The final circuit of the VHF bridge is illustrated in Figure 106. The physical appearance of the bridge is shown in Figure 107. Although the circuit is not unique, the construction represents a radical departure from that



1. TS-15 (OR EQUIVALENT)
2. IFI MODEL 530
3. HEWLETT-PACKARD MODEL 524C
4. VHF BRIDGE (See Text)
5. FULL WAVE (100 MC) TWIN-COAXIAL LINE
6. CRYSTAL UNIT FOR TEST
7. VHF RECEIVER, SERVO MODEL R-5200
8. RECTIFIER (See Text)
9. HONEYWELL MODEL 104W1G

Figure 104. Block Diagram of the Frequency Measuring Equipment for 100 Mc/Sec.

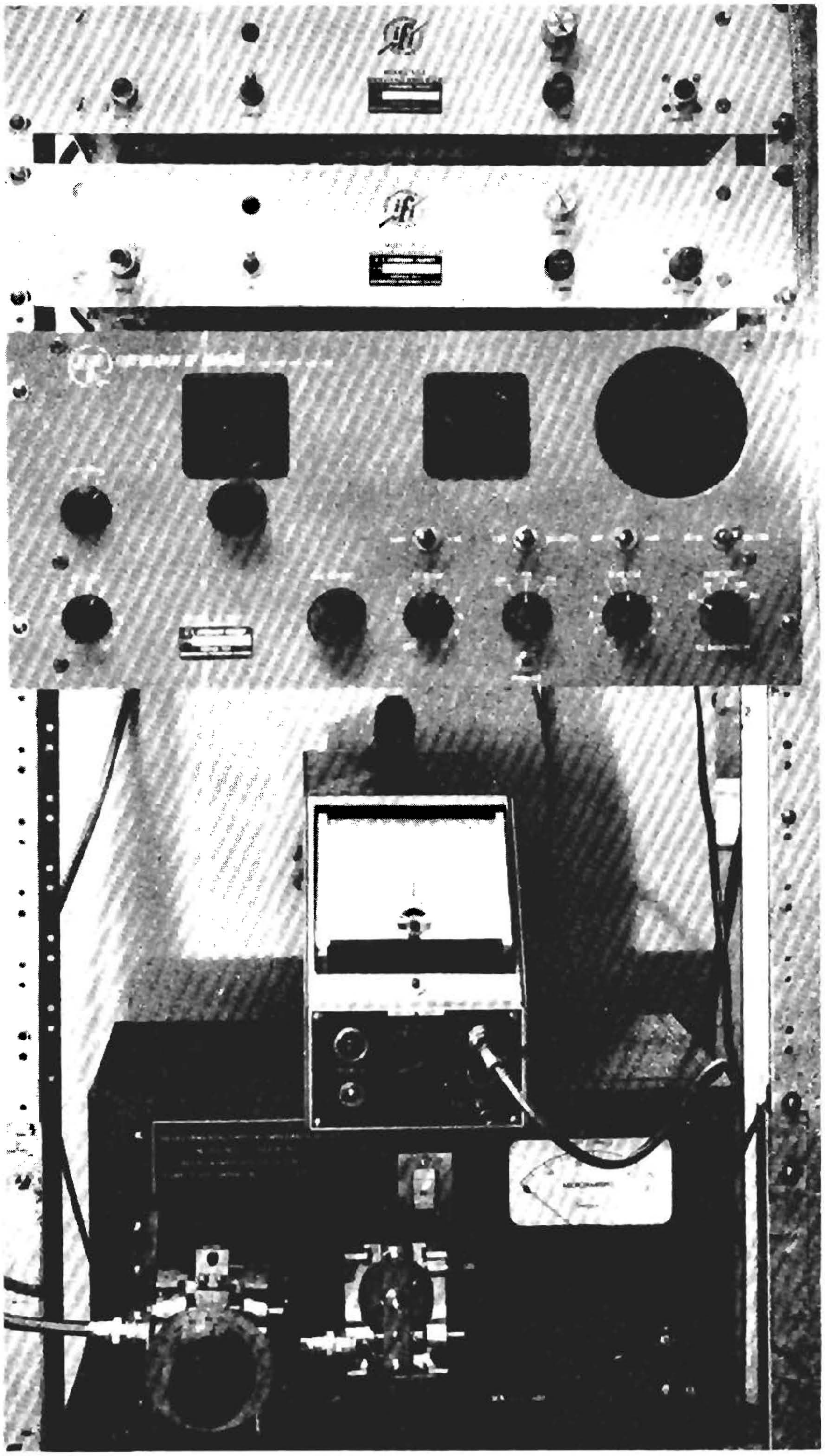
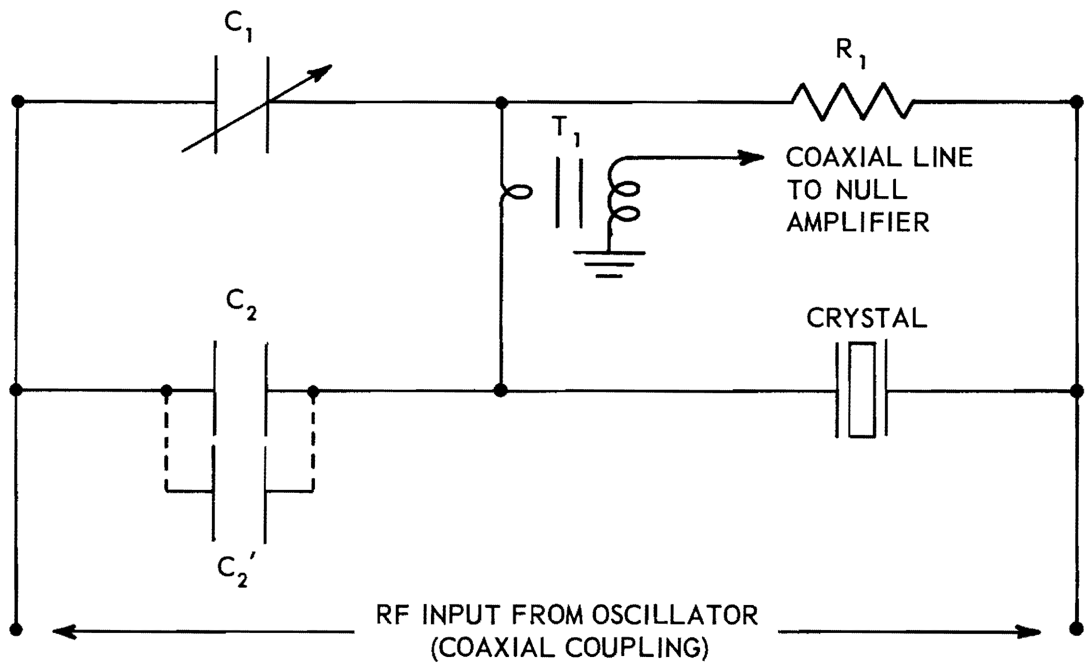


Figure 105. Frequency Measuring Equipment for 100 Mc/Sec.



C_1 – AIR DIELECTRIC 2.7 TO 19.6 $\mu\mu$f

C_2 – SILVERED MICA 10 $\mu\mu$f

C_2' – SILVERED MICA 15 OR 40 $\mu\mu$f (See Text)

R_1 – COMPOSITION 120 Ω

T_1 – ONE TURN PRIMARY, TWO TURN SECONDARY, FERRITE CORE

CRYSTAL – PROVISION MADE FOR OPERATION DIRECTLY INTO BRIDGE OR AT END OF FULL WAVE TWIN-COAXIAL LINE

Figure 106. Circuit for VHF Bridge for 100 Mc/Sec.

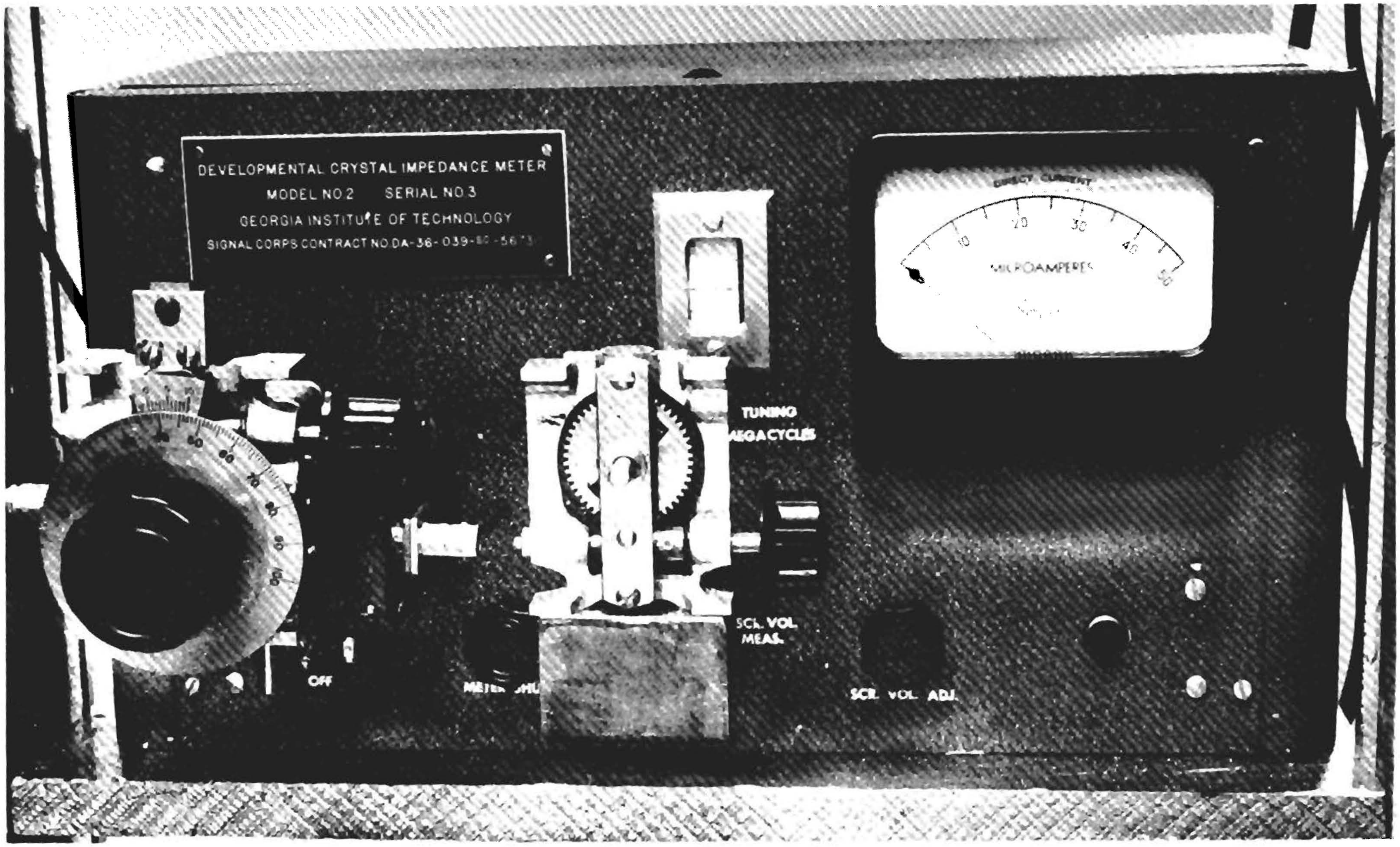


Figure 107. Variable Frequency Oscillator (VFO) and VHF Bridge.

used for radio frequency bridges previously designed and built at Georgia Tech. Each of the four bridge impedances and the ouput transformer were placed in separate compartments of the chassis. It was found that coupling between the various bridge components could thereby be materially reduced with a corresponding increase in the bridge sensitivity. For maximum precision, the tuning shafts of the VFO and variable condenser C_1 (Figure 106) were driven by 40-to-1 antibacklash reduction gears. The bridge and other components of the frequency-measuring equipment have been assembled on a standard 19-inch rack as illustrated in Figure 105. The equipment in the rack obtains power through a constant voltage transformer. The equipment rack and the frequency counter were mounted on wheels to facilitate moving to the various test positions in the laboratory.

Although a detailed study of the performance of the VHF bridge has not been made, the performance was assessed by repetition and by comparison of frequency measurements made with the VHF bridge and measurements made on the same 100-mc/sec crystals by other means.

The mathematical equation for the circuit for Figure 106 at balance follows:

$$\frac{X_{c_1}}{R_1} = \frac{X_{c_2}}{R_s}\ , \text{ or } R_s = \frac{X_{c_2} R_1}{X_{c_1}} \text{ ohms} \tag{1}$$

Since the phase angles of the impedances are

$$\tan^{-1}\phi_s = \frac{X_{c_1}}{R_1} \quad \text{for the shunt branch} \tag{2}$$

and

$$\tan^{-1}\phi_c = \frac{X_{c_2}}{R_s} \quad \text{for the crystal branch,} \tag{3}$$

the branch currents must be in phase. Thus, provided the conditions established by (1) can be realized, a balance will be obtained with respect to both the magnitude of the bridge impedances and the phase of the branch currents.

The balance range of C_1 was subsequently determined. An air dielectric trimmer having a range of 2.7 to 19.6 μμf was selected for C_1. Therefore X_{c_1} = 590 ohms (max), 80 ohms (min) at 100 mc/sec.

When C_2 = 10 μμf (X_{c_2} = 160 ohms) the range of R_s values which satisfy (1) is then 240 ohms (max) and 33 ohms (min). Although it appeared that such a range of R_s values would be adequate, it was found by experiment that stray reactances modified the calculated range to the extent that it was necessary to pad C_2 in order to cover the lower resistance end of the anticipated R_s range. Silvered mica capacitors of 15 and 40 μμf were each mounted in HC-6/U crystal holders and used as a plug-in to increase the value of condenser C_2. With effective values of 10, 25, or 50 μμf for C_2, this arrangement satisfied the balance equations for R_s values from about 10 ohms to over 250 ohms.

At the time of construction only a few 100-mc crystals (fifth overtone units) were available for measurements. Table XI gives the information obtained during measurement of the frequencies and resistances of four of these crystals by three methods. It should be noted that the crystals were plugged directly into the VHF bridge, since the full wave transmission line was not used for this comparison study. The excellent sensitivity and repeatability of the VHF bridge was apparent during the experiment. The bridge was adjusted to within ± 2 cycles of the indicated frequency on repeated trials.

TABLE XI

COMPARISON OF MEASUREMENTS OF FREQUENCY AND RESISTANCE

Crystal No.	VHF Bridge† Frequency (Cycles)	VHF Bridge† C_1 Dial Setting	A-151 Bridge†† Frequency (Cycles)	A-151 Bridge†† R_s (Ohms)	CI Meter Substitution Frequency (Cycles)	CI Meter Substitution R_s (Ohms)
1	100 001 700	48.5	100 001 866	45	100 001 929	58
2	100 000 455	11.0	100 000 528	24	100 001 470	38
3	99 998 556	42.0	99 998 595	39	99 999 096	55
4	100 000 582	36.5	100 000 644	35	100 001 239	55

NOTE: C_o was not compensated. A compensated VHF rheostat was used for the measurements made with the A-151 bridge and for the CI meter substitution measurements.

† C_2 = 25 μμf.

†† Bridge developed under Contract No. DA-36-039 SC-71191.

(2) The Coaxial Connector Line. The full-wave twin coaxial line with BNC terminations at each end was then adjusted to length. The previously measured crystals were connected to the ends of lines known to be too long and the frequencies and resistances (C_1 dial setting) were again measured. All measurements were made with the bridge at balance. The lines were then shortened by known amounts until the crystal frequencies and resistances agreed as closely as possible with the original measurements in the bridge. With a little practice the frequencies were made to agree within five parts in 10^7, and the resistances were made to agree to within 5 percent. Impedance-matching units inserted into the lines to accomplish the electrical adjustment of the line length did not afford the desired precision of adjustment and were discarded.

(3) The Rectifier. The rectifier (No. 8, Figure 104) consists of a simple diode circuit for rectification of the 5-mc/sec IF output of the receiver to a form suitable for driving the null detector, a Minneapolis-Honeywell Model 104 WIG.

(4) Comments. The measurement and control of the amplitude of vibration of the crystal units being measured presented a problem. The differential VTVM Model ME-56/TSM used to measure the voltage across crystals at 16.5-mc/sec was not suitable for use at 100 mc/sec. Automatic gain control for the VFO was applied to the control grid of one of the amplifier tubes. This action did not provide sufficient control. It was then found that a small change in screen voltage had far greater effect than a relatively large change in control grid voltage.

The application of AGC to the screen grid presented an attractive possibility; another solution to the problem of the control of the amplitude of oscillation was tried with excellent success for the few 100-mc/sec crystals available for testing. Consider the arrangement shown in Figure 108. The voltages at points A and B can be measured with good accuracy using a Millivac Model MV-18BRF VTVM. The voltages cannot of course be subtracted directly to obtain the voltage across the bridge due to the phase relations existing at A and B. It was found that it was not necessary to measure both voltages to obtain a constant amplitude of crystal vibration. When the voltage at A is held constant at some predetermined value by controlling the screen voltage, the crystal frequency may be adjusted to within two parts in 10^8 on repeated measurements. The optimum value of the voltage at A was found to be 25 mv. This value is obtained at a screen voltage of about 10 volts.

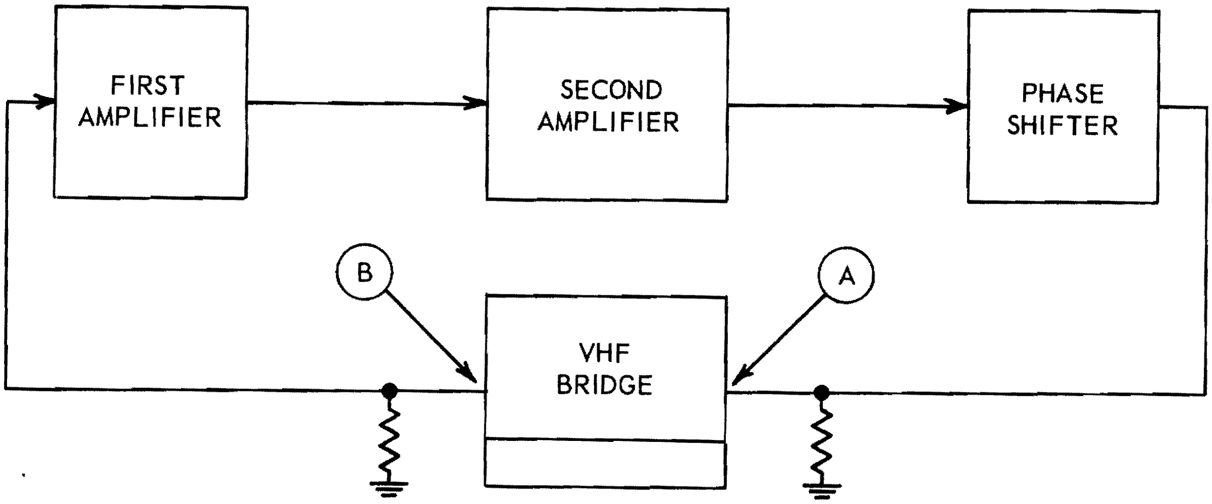


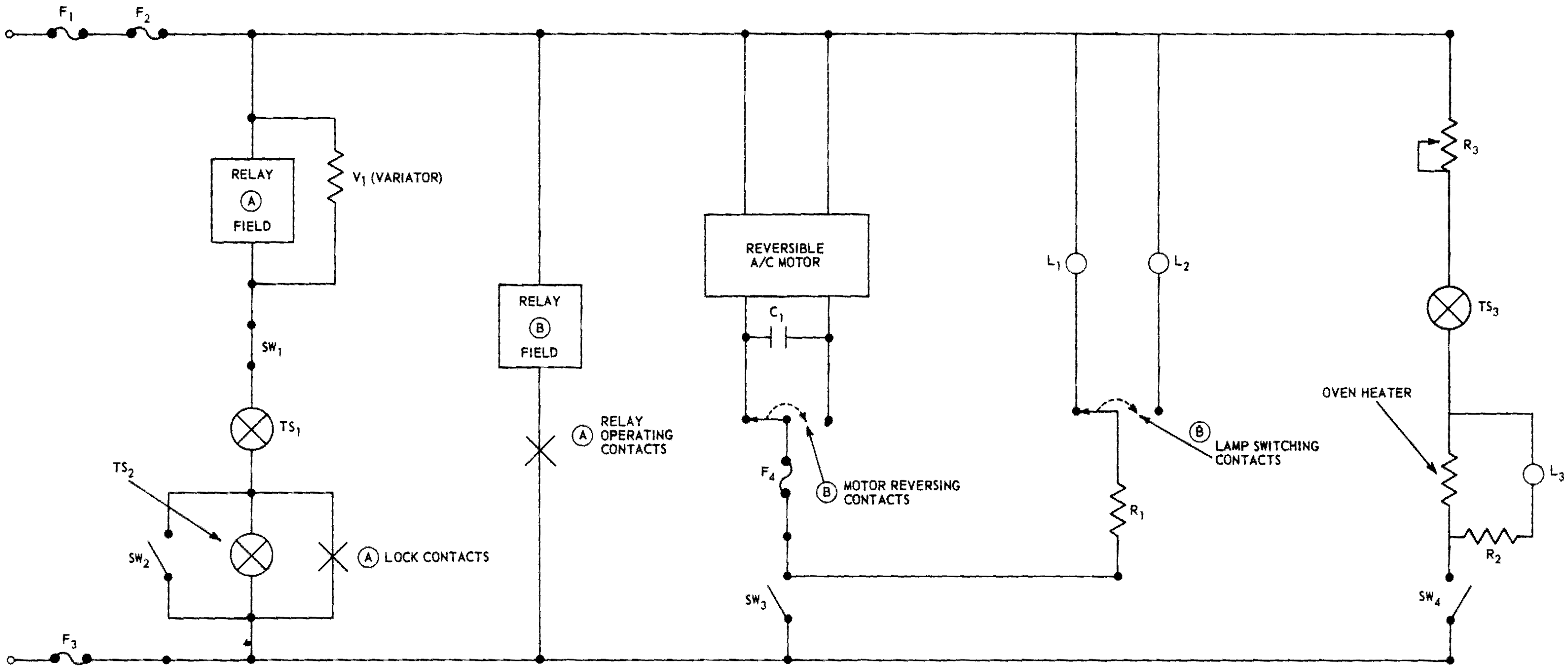
Figure 108. Functional Schematic Diagram of Oscillator and VHF Bridge.

Accurate measurement of crystal aging requires that the amplitude of crystal vibration have a low and constant value. The technique described apparently gives a constant value. It is conjectured that the crystal power is also very low for two reasons. First, the oscillator is operated at very low gain, i.e., a reduction of the screen voltage from 10 volts to about 8 volts causes oscillation to stop. Secondly, when a crystal unit is tuned to null no stabilization period is required before the measurements of frequency can be made. When somewhat higher drive levels are used (i.e., higher voltage at Point A) some time is required for the crystal frequency to reach stability. It is anticipated that the value of 25 mv at Point A will hold for all values of R_s. The required screen voltage will increase, however, as R_s increases.[†]

b. Resonator-Aging Ovens. The temperature-cycling oven and the associated control circuit have been completed. Final testing is being conducted to determine the proper setting of the variable speed control and the oven heater control rheostat. The control circuit schematic is shown in Figure 109. Figure 110 illustrates the oven control panel. The operation of the control circuit was covered in the Interim Report dated 30 June 1959.

The cycling oven consists of two nested boxes formed of 1/8-inch aluminum sheet. The inner box was provided with a heater on the outer vertical walls. The heater consisted of 10 turns of 28-gauge Chromel "A" wire bonded to the aluminum with a refractory cement. The crystals to be temperature cycled are stored inside of the inner box. The outer box, shown in Figure 111 has 1/4-inch wool felt on all surfaces. The bimetallic thermostat, the two mercury thermostats, a temperature sensitive fuse, a thermocouple and the variable-speed reduction gear are mounted on the lid of the outer box. The temperature-sensing elements extend through each lid into the crystal storage compartment.

[†] No implication is intended that all crystals would operate at the same drive level. Rather, the RF voltage across the crystals should increase with R_s provided the voltage at Point A (Figure 108) is held constant. This action need not reduce the quality of the information obtained from high resistance units provided the drive level is sufficiently low.



RELAYS
- A – SPDT (HIGH RESISTANCE FIELD)
- B – DPDT

THERMOSTATS
- TS_1 – 0°C FIXED CONTACT MERCURY
- TS_2 – 55°C FIXED CONTACT MERCURY
- TS_3 – ADJUSTABLE, BIMETALLIC

SWITCHES
- SW_1 – SPST NORMALLY CLOSED
- SW_2 – SPST NORMALLY OPEN
- SW_3 – SPST
- SW_4 – SPST

FUSES
- F_1 – 5 AMPS
- F_2 – (TEMPERATURE SENSITIVE)
- F_3 – 5 AMPS
- F_4 – 5 AMPS

RESISTORS
- R_1 – 39 K OHMS
- R_2 – 39 K OHMS
- R_3 – 25 OHMS RHEOSTAT

LAMPS
- L_1, L_2, L_3 – NE51 LAMP

NOTE: RELAY CONTACTS ARE INDICATED BY THEIR FUNCTION AND OPERATING FIELD.

NOTE: THE VARIABLE RATIO REDUCTION GEAR WHICH DRIVES TS_3 AND IS DRIVEN BY THE A/C MOTOR IS NOT SHOWN.

Figure 109. Control Circuit for Temperature Cycling Oven (0° to 60° C).

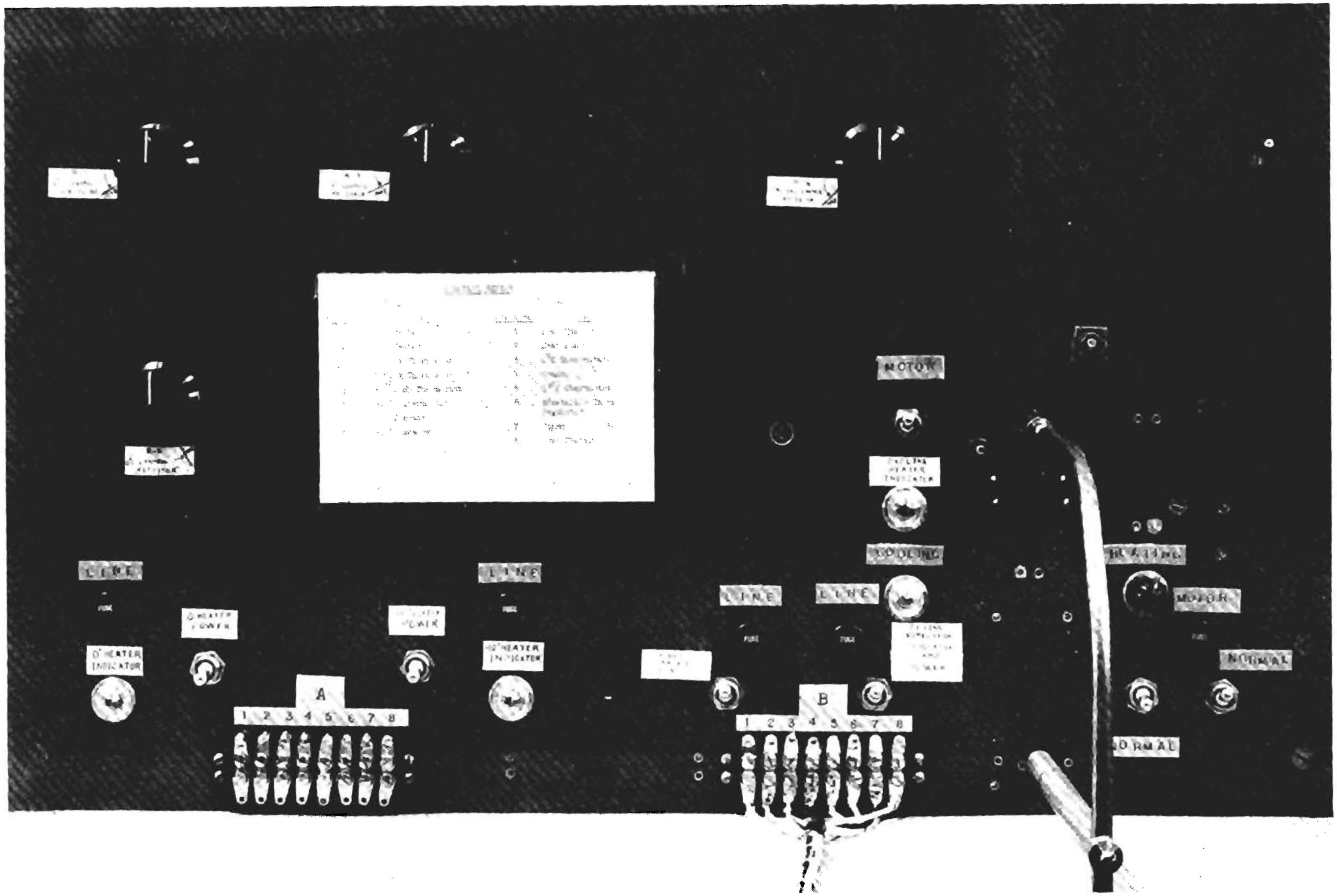


Figure 110. Control Panel for the Temperature Cycling Oven (0° to 60° C).

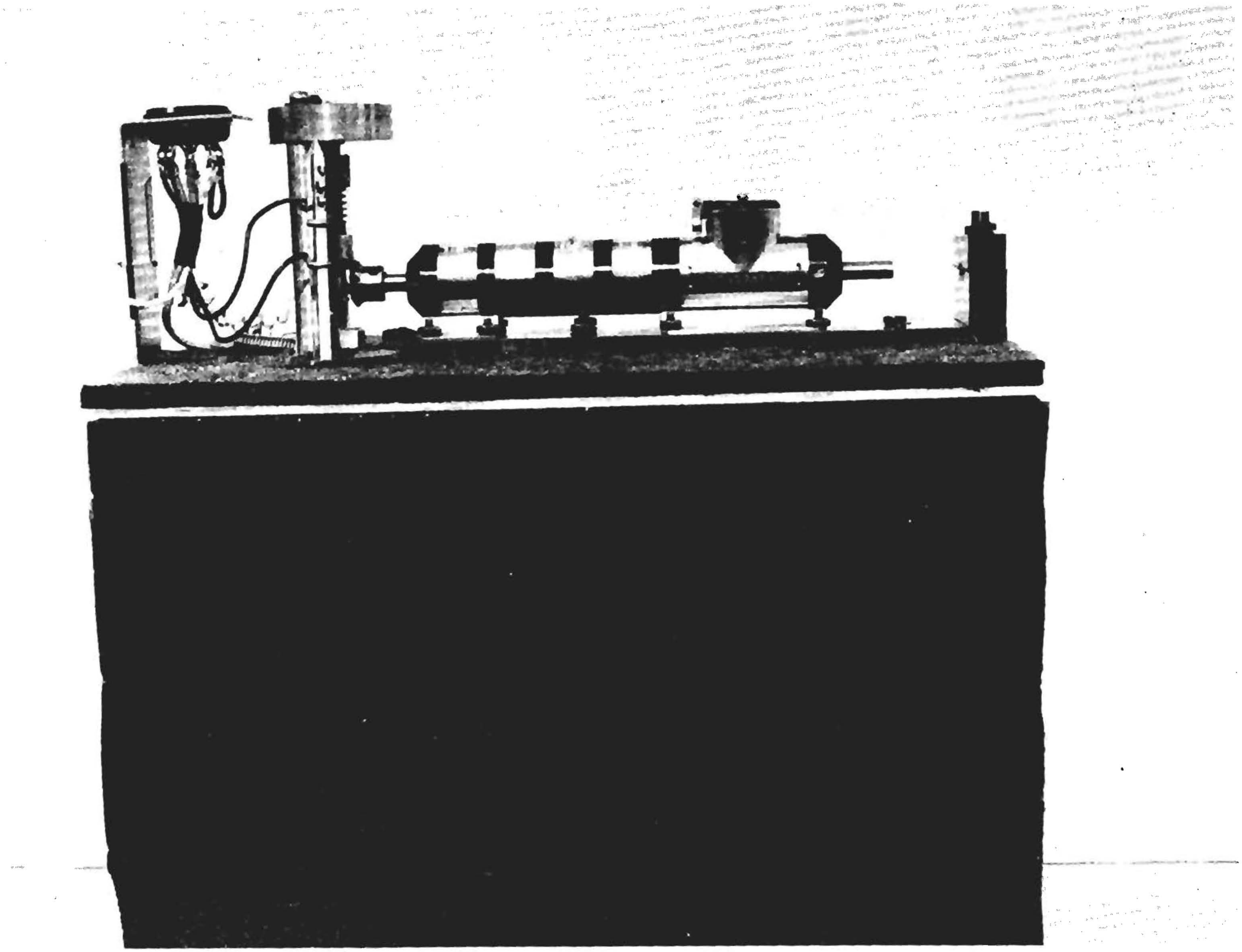


Figure 111. Temperature Cycling Oven Thermostat Drive and Speed Reducer on Top.

The two fixed temperature ovens (0° and 60°C) are presently under construction and the 60°C oven is nearly complete as shown in Figure 112. Each of these ovens has 36 test positions. Twin coaxial lines will be used to connect the test positions to BNC sockets mounted on the bottom of the outer box. Otherwise, the general design of the oven and control circuits will be the same as that of the 85°C constant temperature oven constructed under Contract No. DA-36-039 SC-78910.

c. Apparatus and Procedures for Fabrication of 16.5-Mc Resonators. A quartz crystal of the type studied is exhibited in Figure 113. It consists of a 16.8-mc polished blank 0.45 inch in diameter furnished by a commercial quartz crystal supplier.

The quartz was carefully cleaned by immersion in hot chromic acid solution, thorough rinsing in hot distilled water, final rinsing in methyl alcohol, and drying with hot air. It was placed in an aluminum mask, with the usual keyhole patterns, and inserted in the vacuum chamber. Both sides of the blank were heated by radiant heating to 450°C and then cooled to 250°C; this temperature was held for 10 minutes prior to evaporating aluminum simultaneously onto each side of the quartz.

After cooling the quartz blank and removing it from the vacuum chamber, the blank was mounted on a glass lamp stem by means of .006-inch diameter spring clips which were soldered to the leads of the stem with high-melting-temperature lead solder. The crystal was bonded to the clips by means of Hanovia No. 2 silver cement. The stem, with crystal attached, was sealed to the glass envelope on a lathe having a vertical axis of rotation.

Resonators completed to this stage were then connected to a vacuum system by insertion of the respective tubulations through rubber stoppers

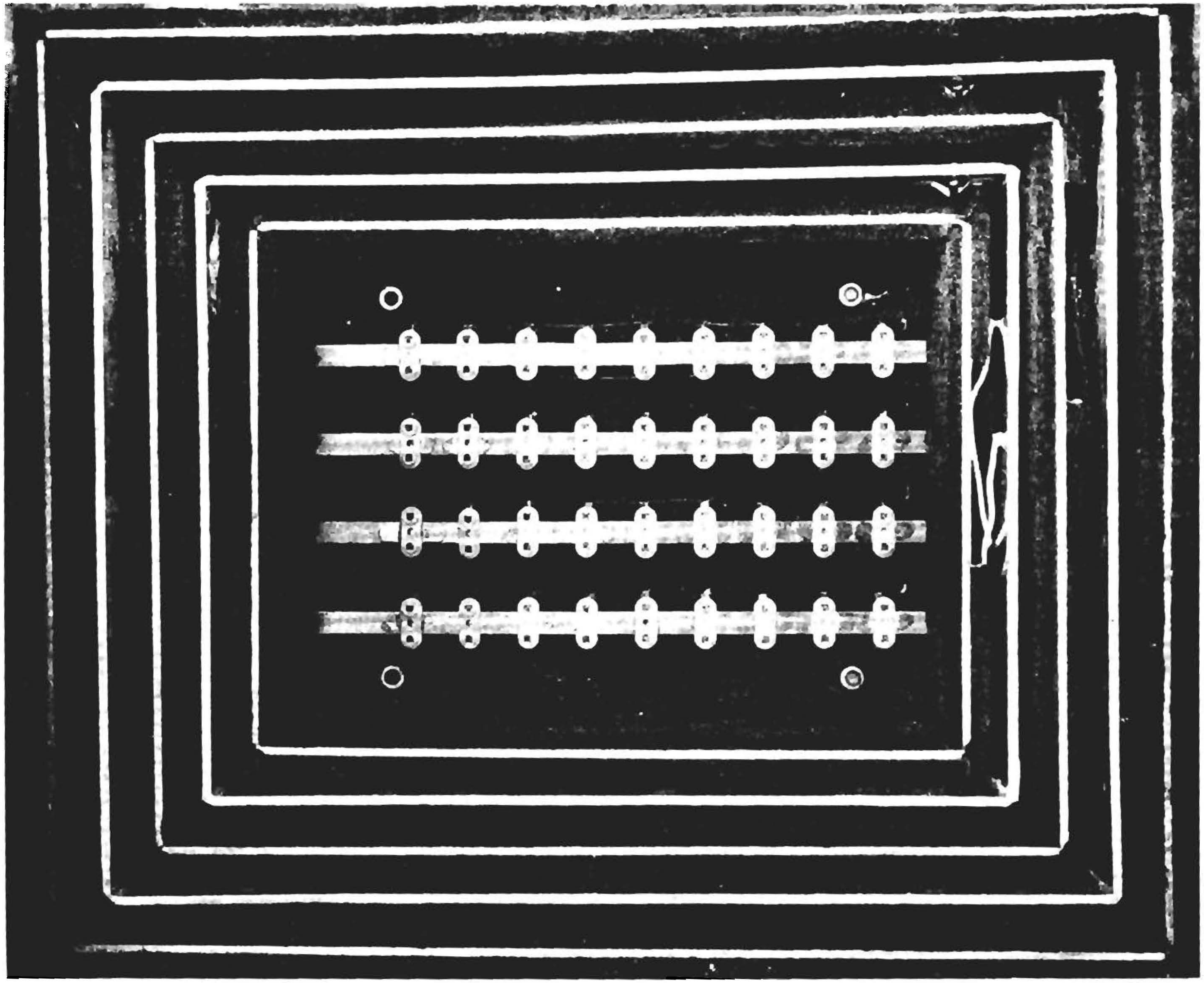


Figure 112. Interior of 60° C Constant-Temperature Oven.

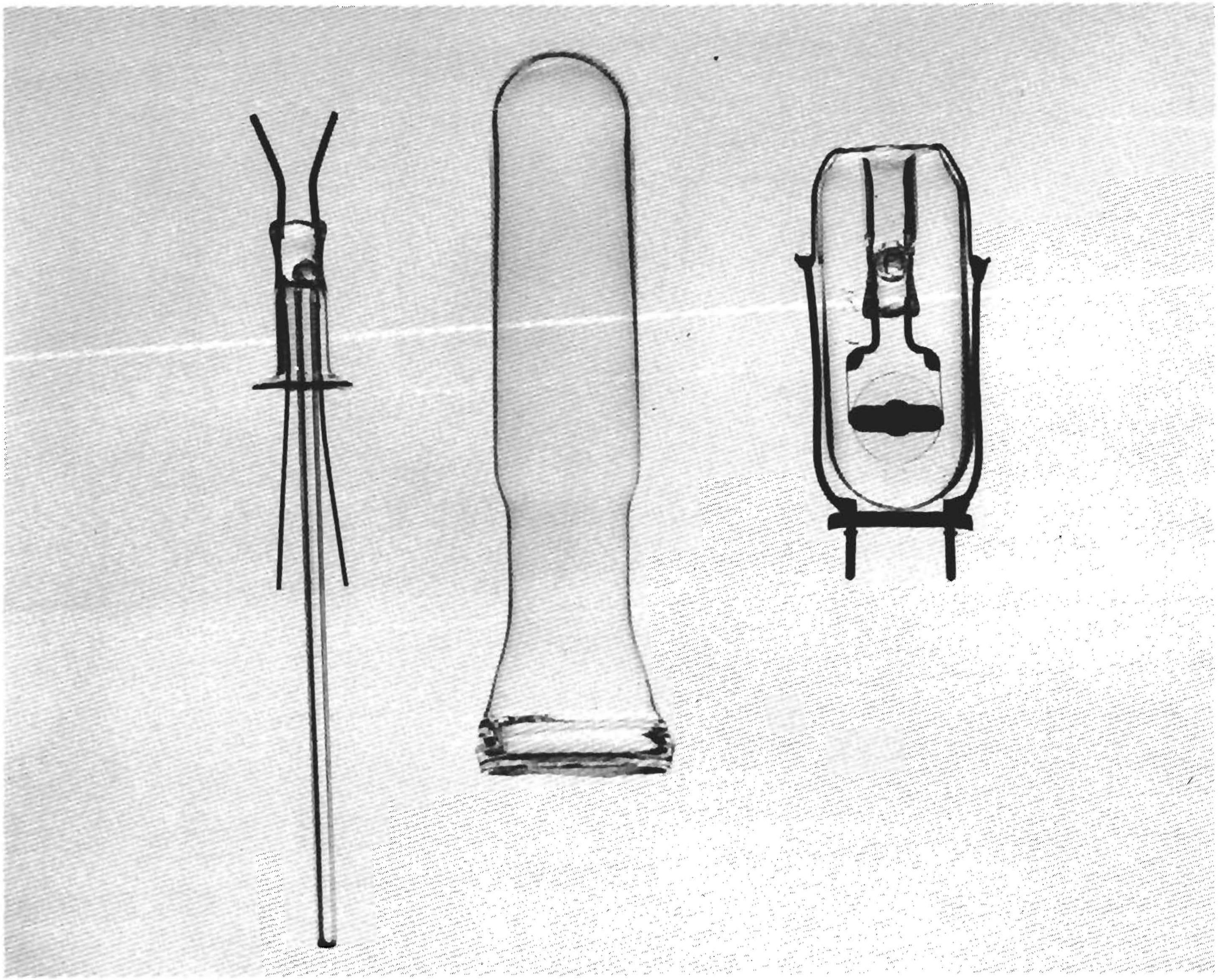


Figure 113. 16.5 Mc Resonator Mounted in Glass Envelope.

in the header plate. A demountable oven placed over the resonators allowed baking of the units while connected to the vacuum chamber. Bakeout was generally conducted for periods of about 3 hours at 180°C and at pressures of 5×10^{-6} mm of mercury.

The procedure given applies only to the base plating of units. When resonators were plated a second time for frequency adjustment this was done at the completion of the bonding of the resonator into the spring clips but before encasing it in the envelope. Overplating was done at room temperature or at a selected temperature, designated for the unit group. The overcoated units were then baked *in vacuo* and sealed in the manner described for the units which were base plated only.

The resonators were stored in an oven maintained at 85° ± 0.01°C. Frequency and R_s measurements were made initially, after 24 hours, and daily for 15 days. Thereafter, measurements were made once or twice per week. The resonators were operated only during the period of measurement.

Frequency measurements were made by the bridge method previously described.[†] A Western Electric Oscillator, 0-76U, was the standard frequency source. The standard was checked daily against WWV; the accuracy of comparison is considered to be within a few parts in 10^8 per day. The long term drift of the oscillator 0-76U has been measured as a few parts in 10^9 per day. The daily measurements of the resonators were accurate to within two

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[†] R. B. Belser, "Study of the Effects of Processing Techniques and Materials of Aging of Quartz Crystals," Final Report, Contract No. DA-36-039 SC-64613, USASRDL, Ft. Monmouth, N. J., 1 July 1957.

D. W. Robertson, "Investigation of Methods for Measuring the Equivalent Electrical Parameters of Quartz Crystal Units," Final Report, Contract No. DA-36-039 SC-71191, USASRDL, Ft. Monmouth, N. J.

parts in 10^7.

3. Experimental Work

a. Introduction. It has been shown previously[†] that AT-cut quartz resonators of about 16.5-mc frequency, operated in the fundamental mode, can be readily fabricated to maintain frequency stabilities exhibiting drifts of less than one part per million per year. Whereas such stabilities can be maintained by gold-plated units mounted in either glass or metal containers, stabilities of the same quality have not been achieved, except in rare instances, for aluminum-plated resonators.

The importance of aluminum plating lies in its low density coupled with its excellent electrical conductivity. These properties adapt it particularly to use for the plating of units to be oscillated at the overtone modes in the frequency ranges near 100-mc or above.

Last year, at the 13th Annual Frequency Control Symposium, initial successes with aluminum-plated resonators were reported by the authors, and the problem of the effect of overplating to frequency on stability was just being considered. In this report a more thorough treatment of overcoating experiments is presented.

[†] R. B. Belser, "Study of the Effects of Processing Techniques and Materials on Aging of Quartz Crystals," Final Report, Contract No. DA-36-039 SC-64613, USASRDL, Ft. Monmouth, N. J., 1 July 1957.

R. B. Belser and W. H. Hicklin, "Study of Aging Effects of Quartz Crystals," Final Report, Contract No. DA-36-039 SC-74946, USASRDL, Ft. Monmouth, N. J. 31 July 1958.

R. B. Belser and W. H. Hicklin, "Effect of Plating to Frequency on the Stability of Quartz Resonators," Proceedings of the 12th Annual Symposium on Frequency Control, USASRDL, Ft. Monmouth, N. J., 608 May 1958.

b. Aluminum-Plated Resonators.

(1) Resonators Base Plated Only. The experimental work was planned to explore the value of aluminum as a plating material for quartz resonators. The primary objective was to determine minimum drift rates that might be expected from units base-plated with aluminum only; a second objective was to devise overcoating techniques which would be expected to result in minimum frequency degradation and yet allow a reasonable frequency adjustment range.

The first stable aluminum-plated resonators produced here were those of group N placed on measurement 22 August 1958. This was the first series of units plated at a substrate temperature of approximately 250°C, baked out *in vacuo* for 3 hours, and mounted in glass. Subsequently a group, designated T, was fabricated similarly with an excellent record of stability as shown in Figure 114 and in Table XI.

The 3-hour bakeout period appeared to be longer than might be economically desirable, but, as shown in the table, groups W and X exposed to bakeouts of 1 or 2 hours were less stable than those of group T. A third set, group Y, baked out for 2 hours exhibited stable behavior, however. It thus appeared that 2 hours approaches the minimum desirable bakeout time at 180°C and approximately 5×10^{-6} mm of mercury pressure.

It is apparent from the examination of Figure 114 and the high percentages of stable units in groups T and Y, as shown in Table XII, that aluminum-plated resonators of high stability can readily be fabricated if mounted in glass containers. Stabilities of resonators similarly prepared but mounted in the HC-6/U metal container were less stable. Data for a typical unit are shown in

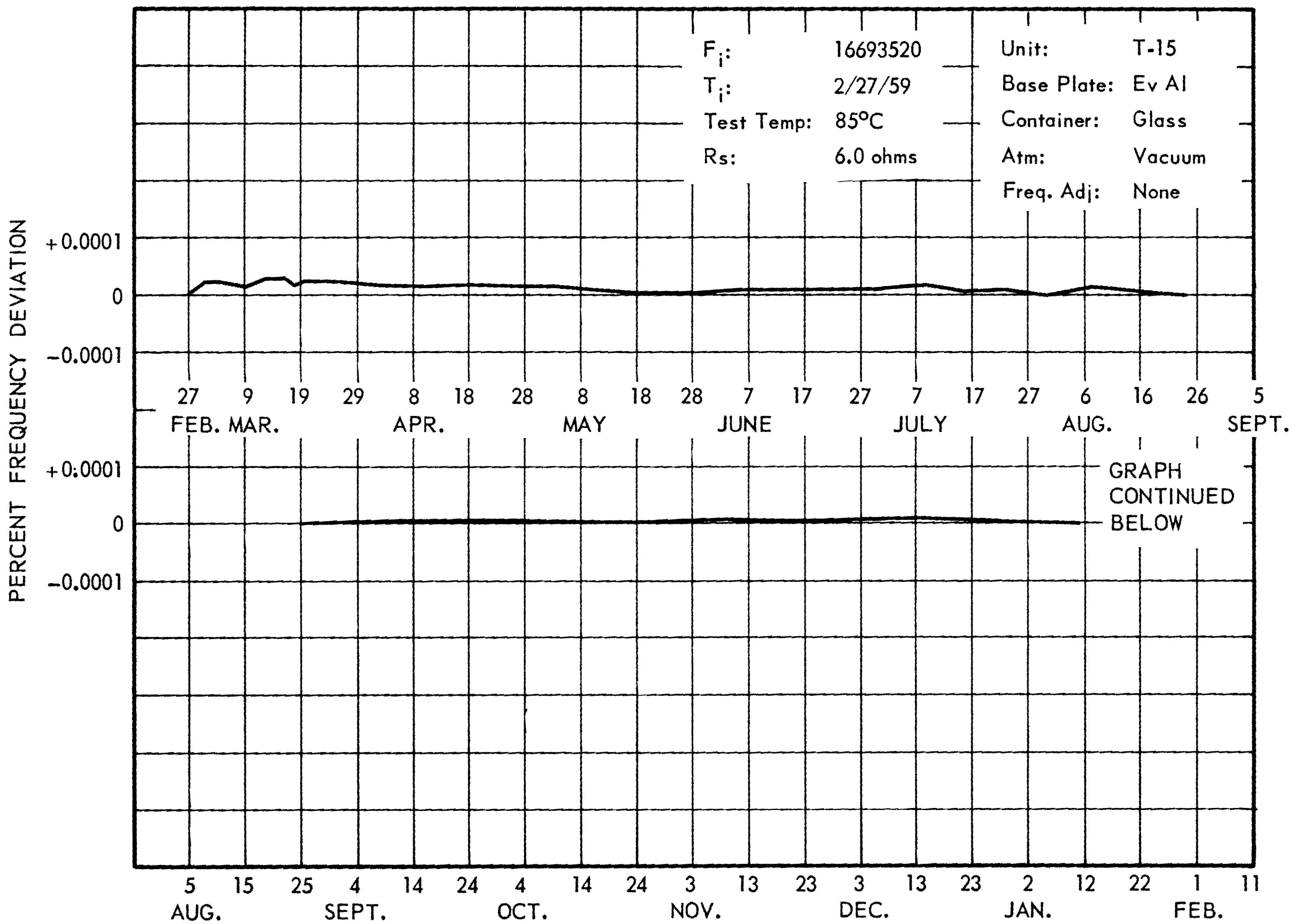

Figure 114. Plot of Frequency Data for Resonator T-15, Al Only, in Glass Container.

TABLE XII

STABILITY ANALYSIS OF 16.5-MC QUARTZ RESONATORS
PLATED WITH ALUMINUM OR OTHER METALS

Group	Plating (Containers)	Days Measured	Total Number of Units	Stability for Period (ppm/yr) <0.5	<1	<2	Number of Units Erratic	Comments
				(Number of Units)				
T	Al only (glass)	324	17	7	13	16	1	
W	Al only (glass) (1 hr)	150	15	0	3	3	1	1-8, 1 hr, 9-15, 2 hr, rebottled
X	Al only (glass)	150	6	0	1	1	3	High R_s, 1 hr bake-out
Y	Al only (glass) (2 hr)	270	9	4	7	7	1	2 hr bakeout
17	Al only (HC-6/U)	40	17	2	2	2	2	First 12 sealed in air
18	Al only (HC-6/U)	30	10	1	2	3	1	
U	Al+Al (glass)	375	16	1	3	12	0	
9	Al+Al (glass)	210	10	4	8	8	2	
Z	Al+Au (glass)	270	8	4	6	6	2	
8	Al+Au (glass)	210	10	1	1	6	1	
7	Al+Ag (glass)	260	10	4	8	8	2	

(Continued)

TABLE XII (Continued)

STABILITY ANALYSIS OF 16.5-MC QUARTZ RESONATORS PLATED WITH ALUMINUM OR OTHER METALS

Group	Plating (Containers)	Days Measured	Total Number of Units	Stability for Period (ppm/yr) <0.5 (Number of Units)	<1	<2	Number of Units Erratic	Comments
11	Al+Ag (glass)	130	16	4	8	10	4	
10	Al+Cu (glass)	180	14	7	10	11	3	
12	Al+Cr (glass)	120	8	0	0	0	1	Sharp drifts
XP-1	Al+SiO (glass)	5	11	0	0	0	0	Very large drifts
14	Sp Au only (glass)	90	4	4	4	4	0	
16	Ev Au only (glass)	55	9	3	3	3	6	Bondmaster seal
19	Ev Au only (glass)	21	6	0	0	6	0	Bondmaster seal, getter, positive slope
15	Sp Ag only (glass)	75	7	4	6	6	1	
13	Cu only (glass)	100	6	4	5	5	1	
V	Ag+Ni (El) (glass)	405	10	0	1	1	3	Large positive drifts
Grand Totals			219	54	91	118	35	
Percentages			100	24.6	41.5	53.6	15.9	

Figure 115. That highly stable units may also be prepared in the metal can is shown by the data of Figure 116. However, the technique of reproducing consistently stable aluminum-plated resonators mounted in the HC-6/U metal container has not yet been established.

(2) Overplated Resonators. With the aluminum base-plating problem solved it was necessary to examine potential overcoating materials which might be used satisfactorily to adjust the aluminum-plated unit to final frequency. Groups of resonators were made up with aluminum, gold, silver, copper, chromium, or silicon monoxide as overcoating materials. Data for typical units are exhibited in Figures 117, 118, 119, 120, 121 and 122; stabilities of the respective groups are recorded in Table XII for Groups 9, Z, 7, 10, 12, and XP.

In spite of some concern over frequency shifts that might occur in specimens coated with bimetal electrodes, no frequency shifts ascribable to alloying of the plating were observed.

Of particular interest are the units of group 9, Al + Al; (See Figure 117); eight of these units exhibited less than one part per million drift in 7 months and only two showed an erratic nature. Those of groups 7 (Al + Ag), 11 (Al + Ag) and 10 (Al + Cu) exhibited similarly excellent stabilities. (Figure 119 and 120; no figure for group 11.)

In contrast to the stable behavior of the preceding units, resonators overcoated with chromium (Figure 121) or silicon monixide (Figure 122) exhibited decided downward drifts. It was evident that the films of each material were picking up gases at a rate sufficient to cause marked drifts and that neither substance would constitute a satisfactory overcoating material for quartz resonators.

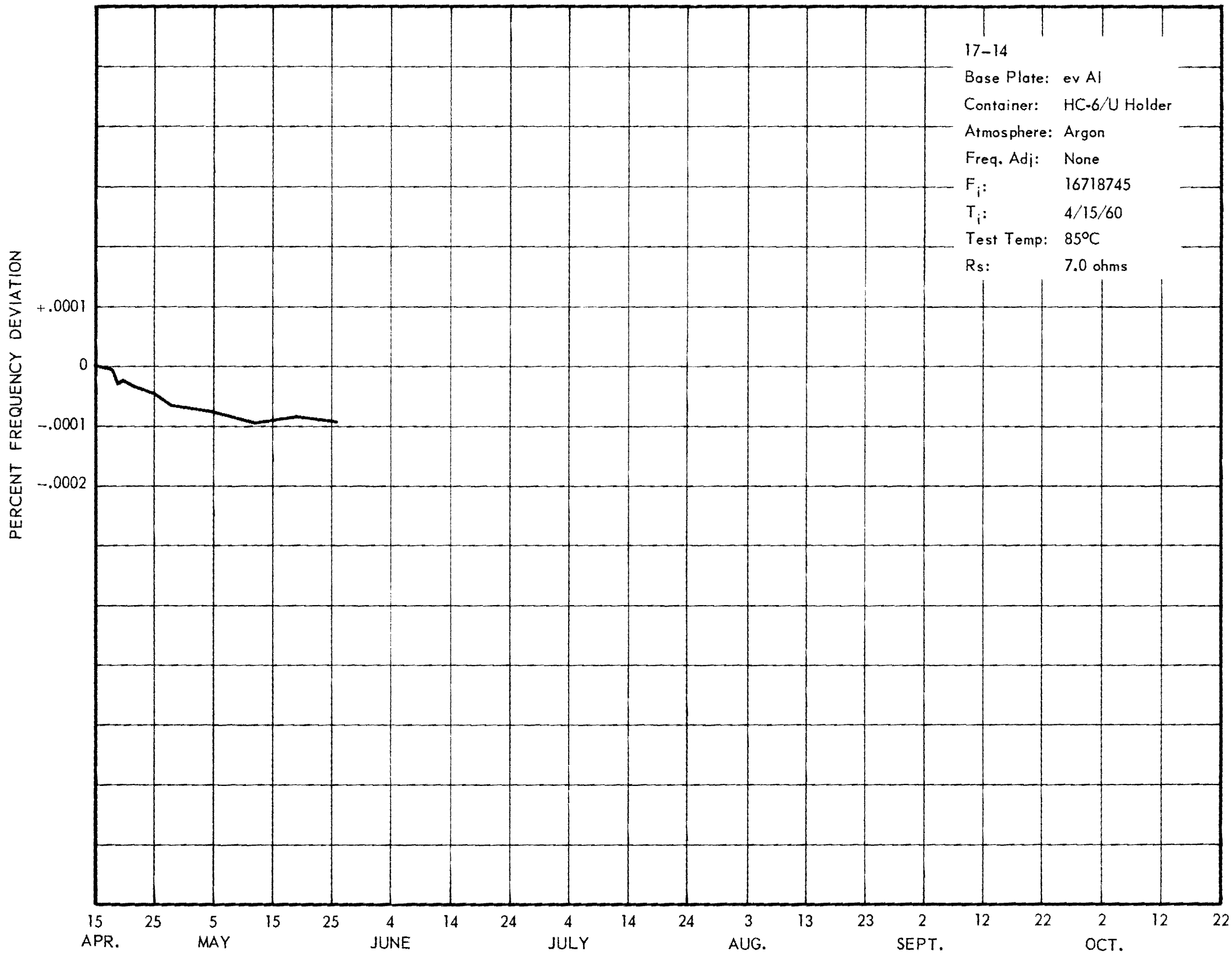

Figure 115. Plot of Frequency Data for Resonator 17-14, Al Only, in HC-6/U Can.

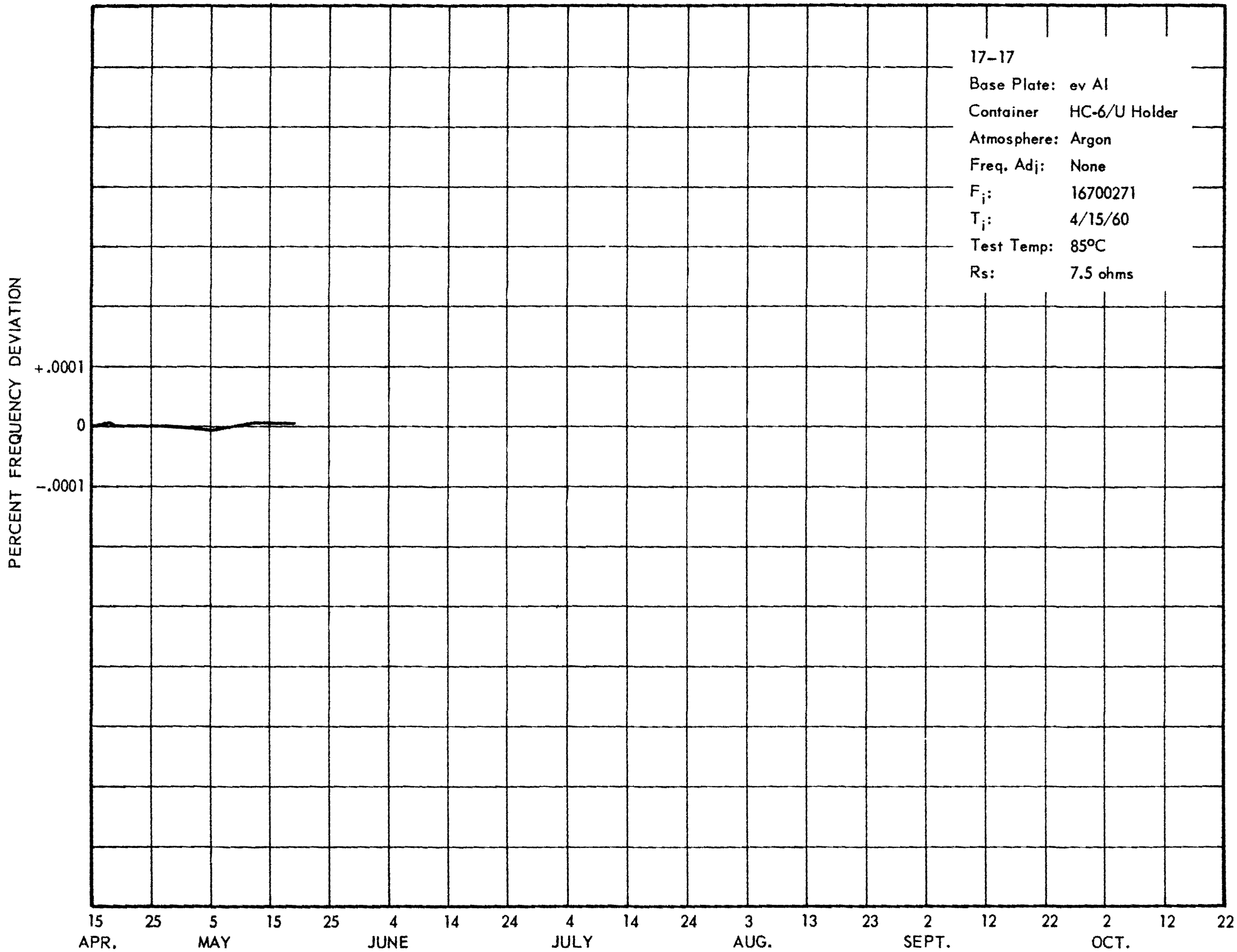

Figure 116. Plot of Frequency Data for Resonator 17-17, Al Only, in HC-6/U Can.

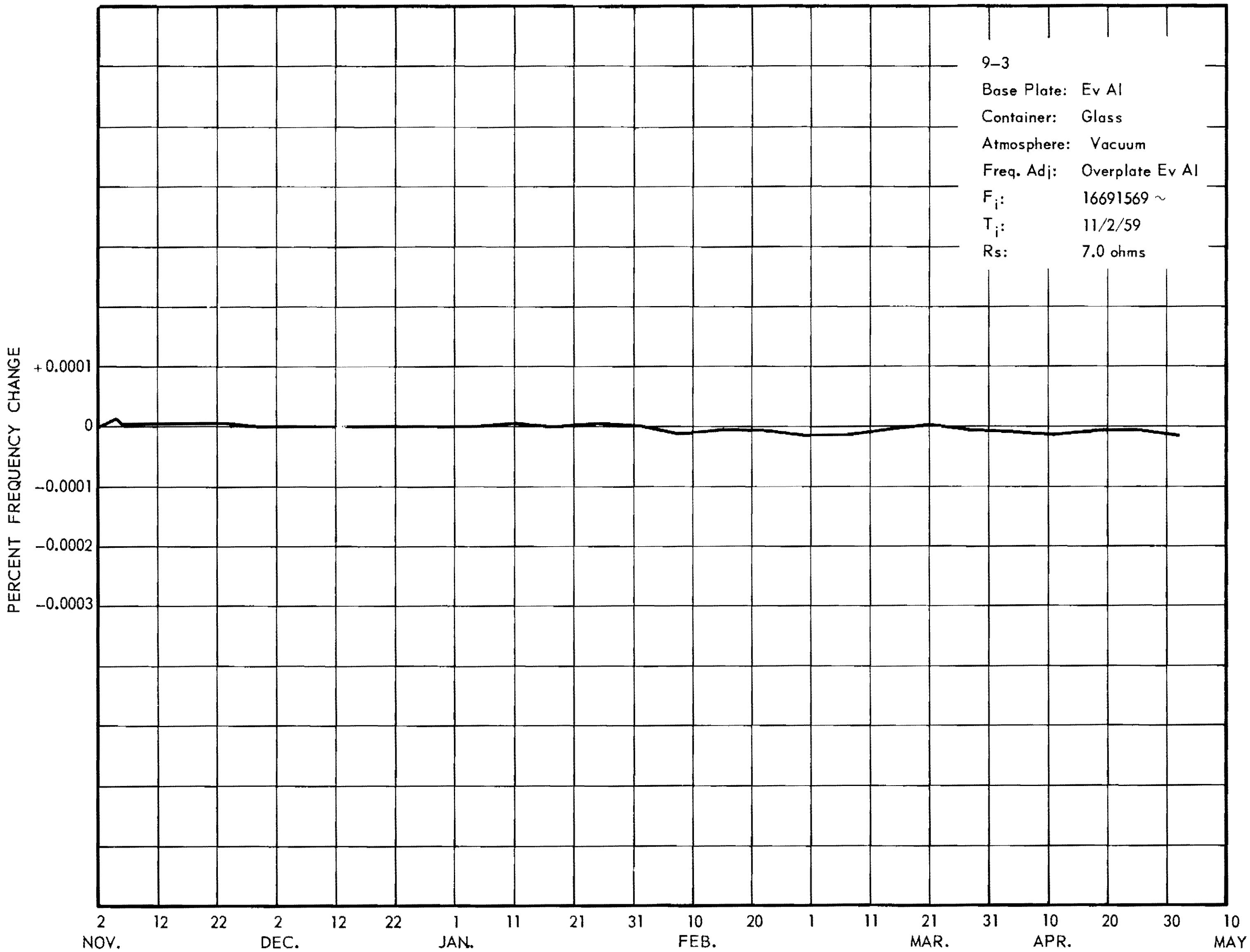

Figure 117. Plot of Frequency Data for Resonator 9-3, Al + Al, in Glass Container.

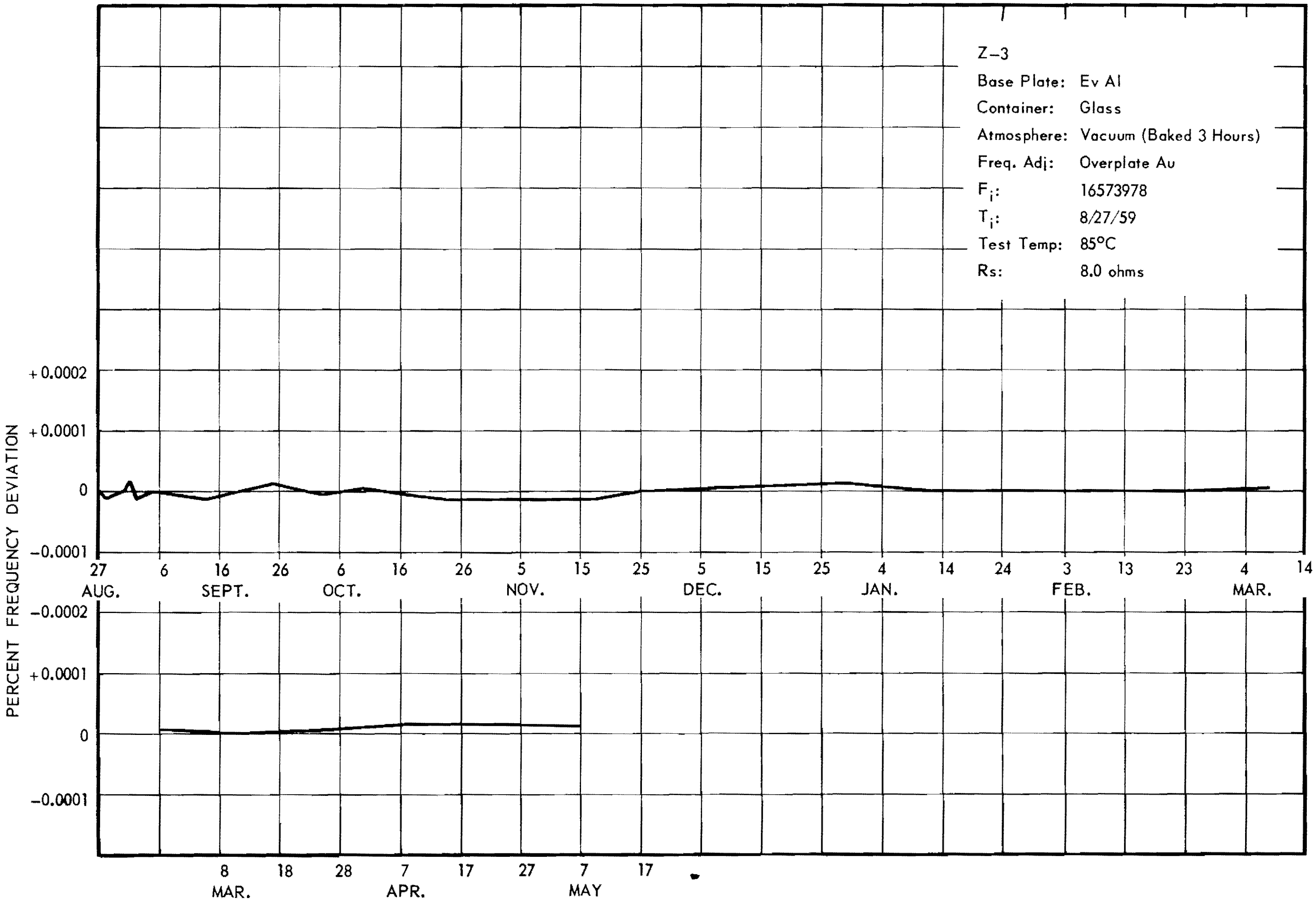

Figure 118. Plot of Frequency Data for Resonator Z-3, Al + Au, in Glass Container.

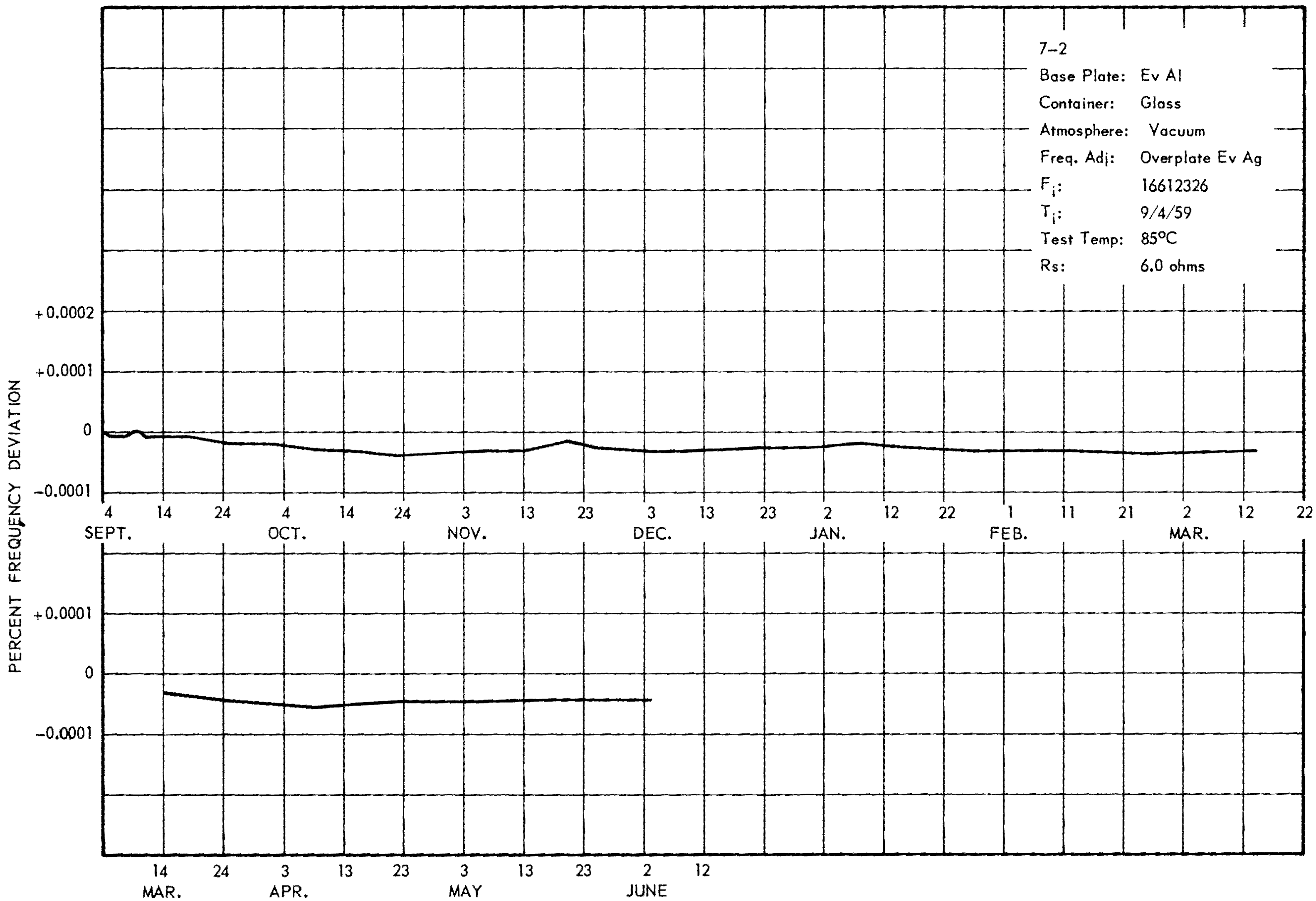

Figure 119. Plot of Frequency Data for Resonator 7-2, Al + Ag, in Glass Container.

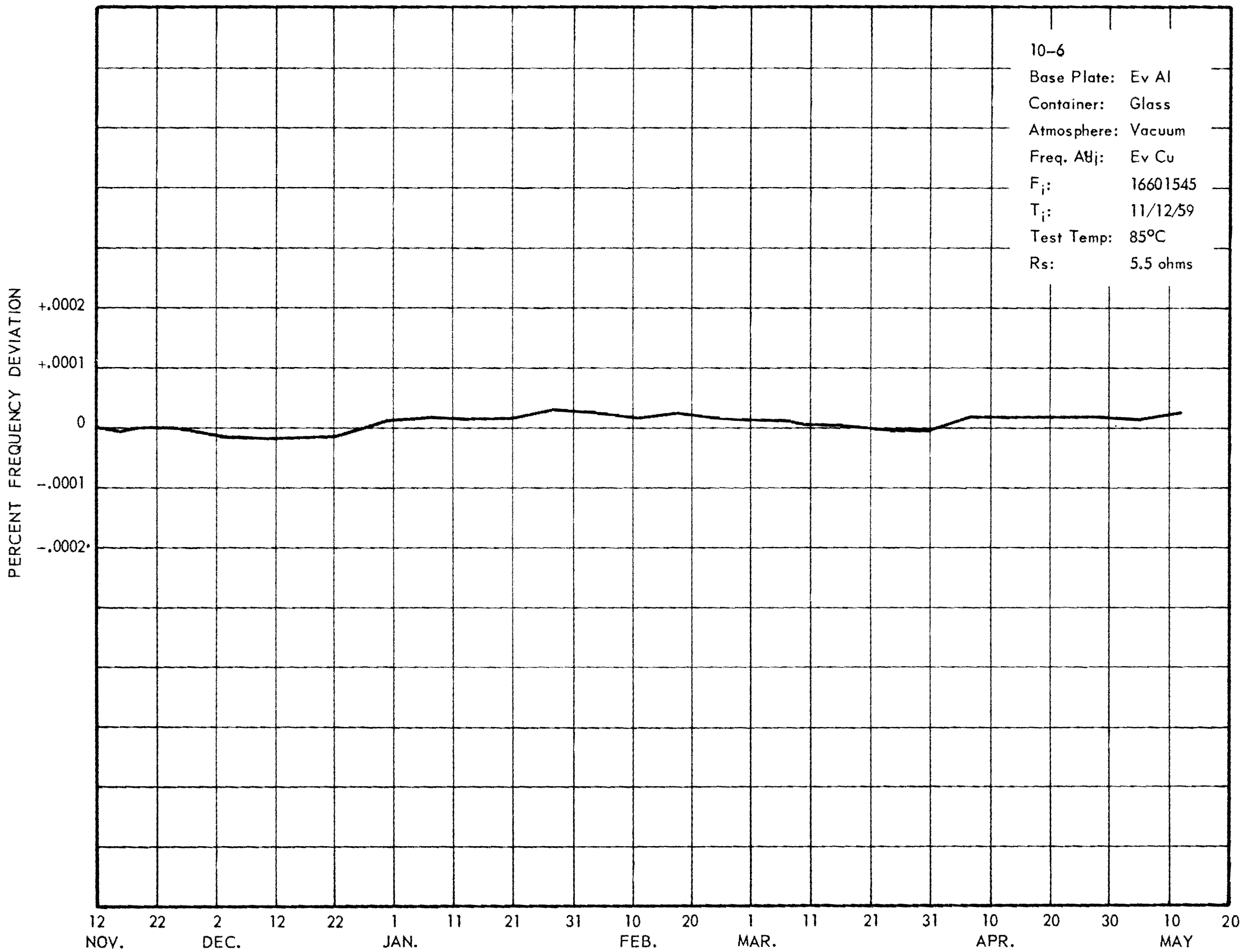

Figure 120. Plot of Frequency Data for Resonator 10-6, Al + Cu, in Glass Container.

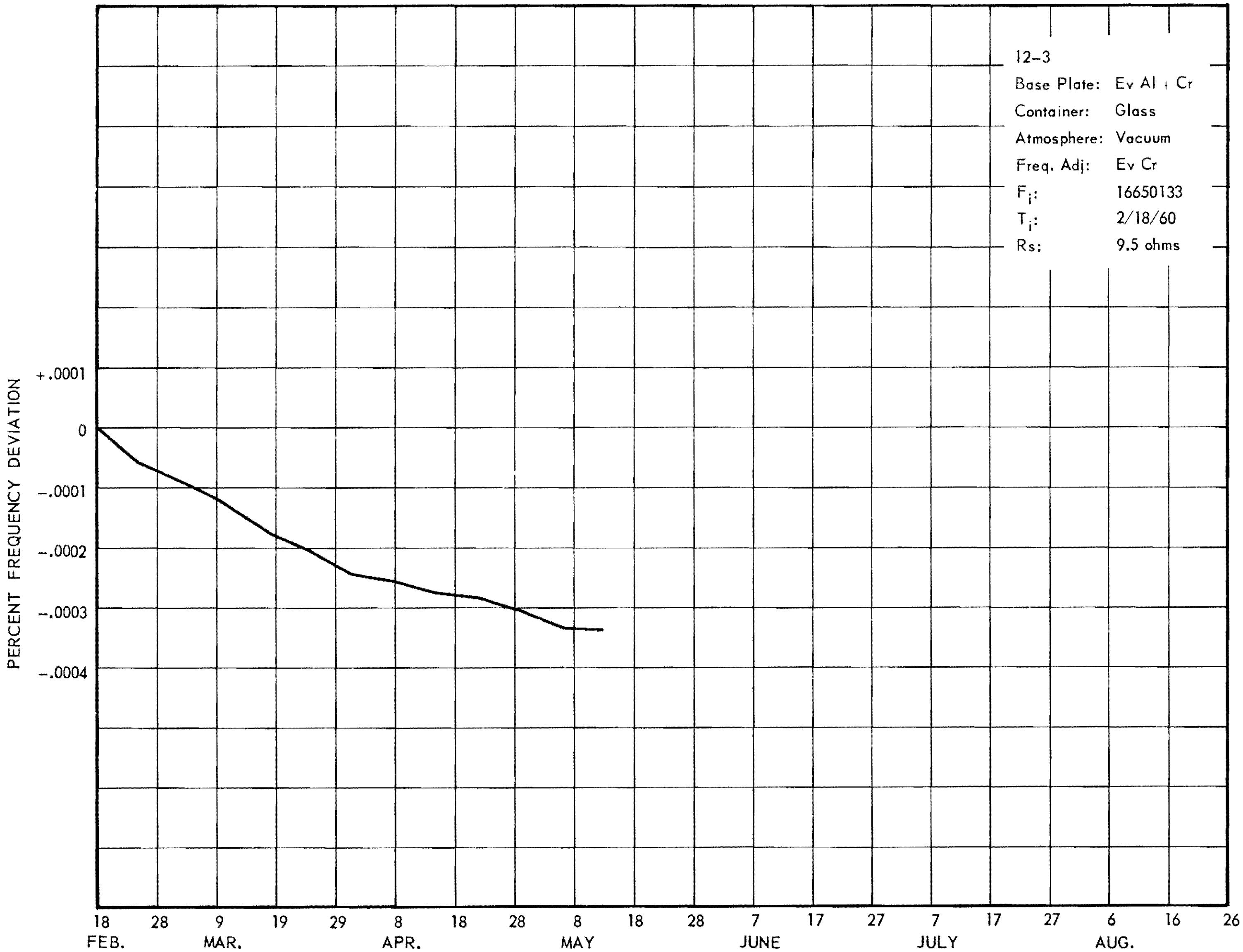

Figure 121. Plot of Frequency Data for Resonator 12-3, Al + Cr, in Glass Container.

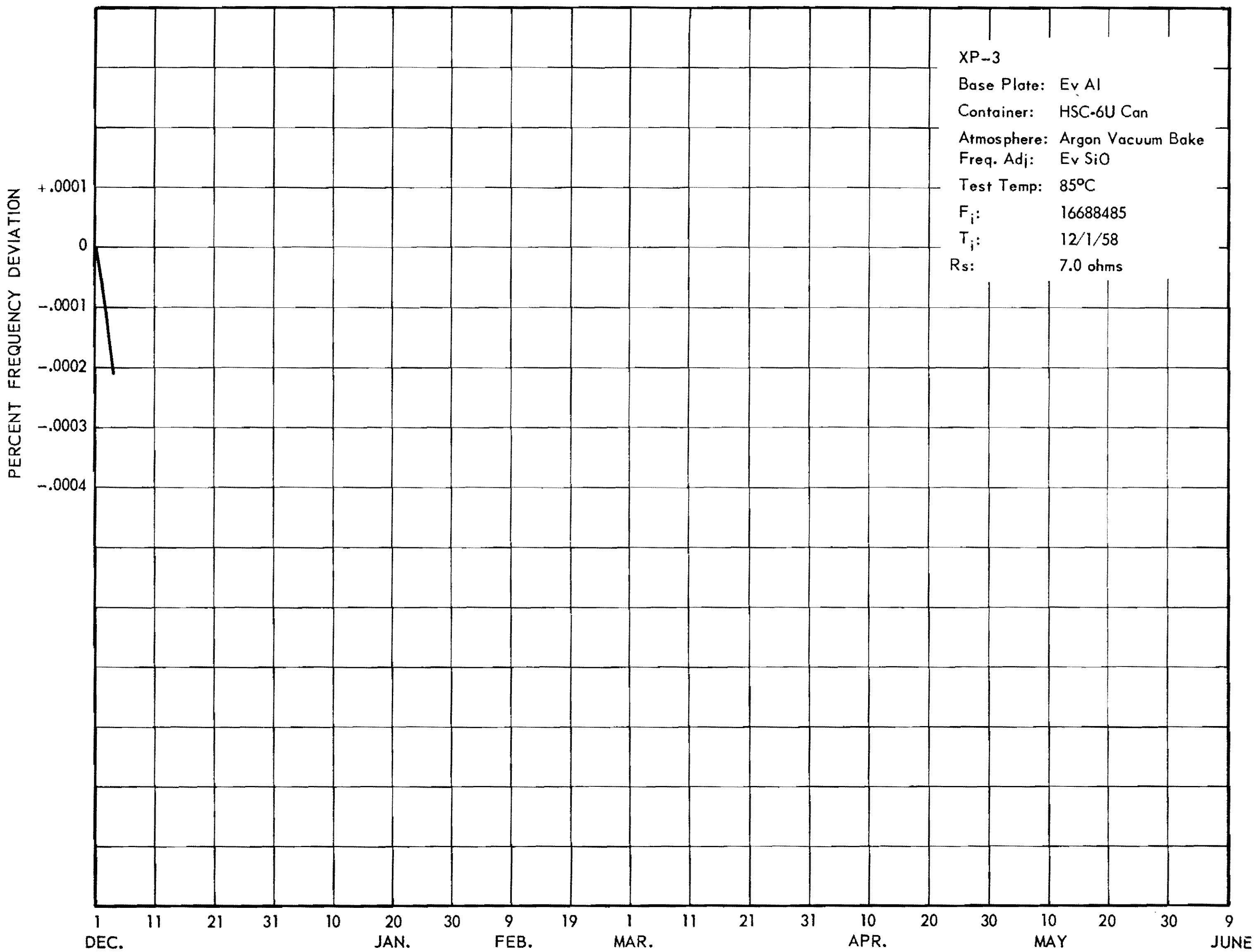

Figure 122. Plot of Frequency Data for Resonator XP-3, Al + SiO, in Glass Container.

c. Resonators Coated with Other Metals. Although the discussions on aluminum-plated resonators are the primary topic of phase III of this report, a review has been made of the stabilities of resonators coated with sputtered gold, sputtered silver, and evaporated copper. Typical stabilities found were excellent; examples of these are exhibited in Figures 123, 124, and 125. The results for copper-coated units indicated that copper is a material which has been overlooked as a crystal-plating metal. Its density of 8.9 and its high electrical conductivity are desirable properties.

A review has also been made of the commonly used bimetal pair Ag + Ni; the silver was deposited by evaporation and the nickel by electroplating. A typical pattern of behavior is shown in Figure 126. The characteristic upward drift appears to be associated with stress anneal in the nickel film; the anneal, in turn, is associated with the thickness of the film and the plating conditions and method. This upward drift may counteract downward drifts due to minor leaks for a period of several months. This behavior appears to explain the adoption of this metal pair by industry. Unfortunately, long-term aging of leaking units of this type is very large. Many examples of typically poor behaviors have been experienced with the some 600 industrially fabricated resonators of which the aging characteristics were studied last year. These characteristics are reported in more detail in a succeeding paragraph. The rapid downward drifts, increasing with temperature of storage, appear to be associated with corrosion by atmospheric gases entering through small leaks enhanced by contact of the nickel with silver.

An additional experiment of interest was the sealing of gold-coated resonators into a glass envelope to which the base was attached by means of

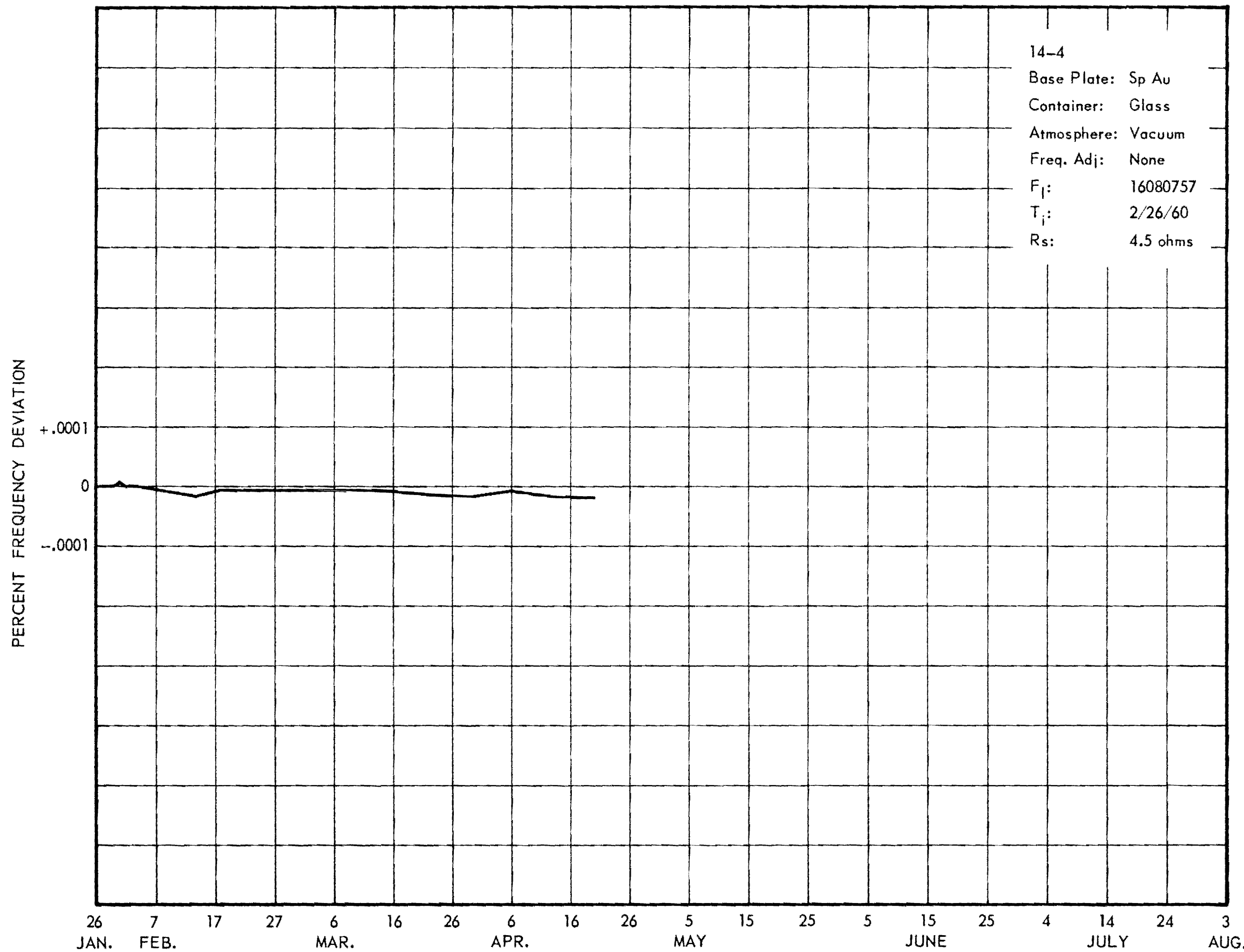

Figure 123.. Plot of Frequency Data for Resonator 14-4, Sp. Au Only, in Glass Container.

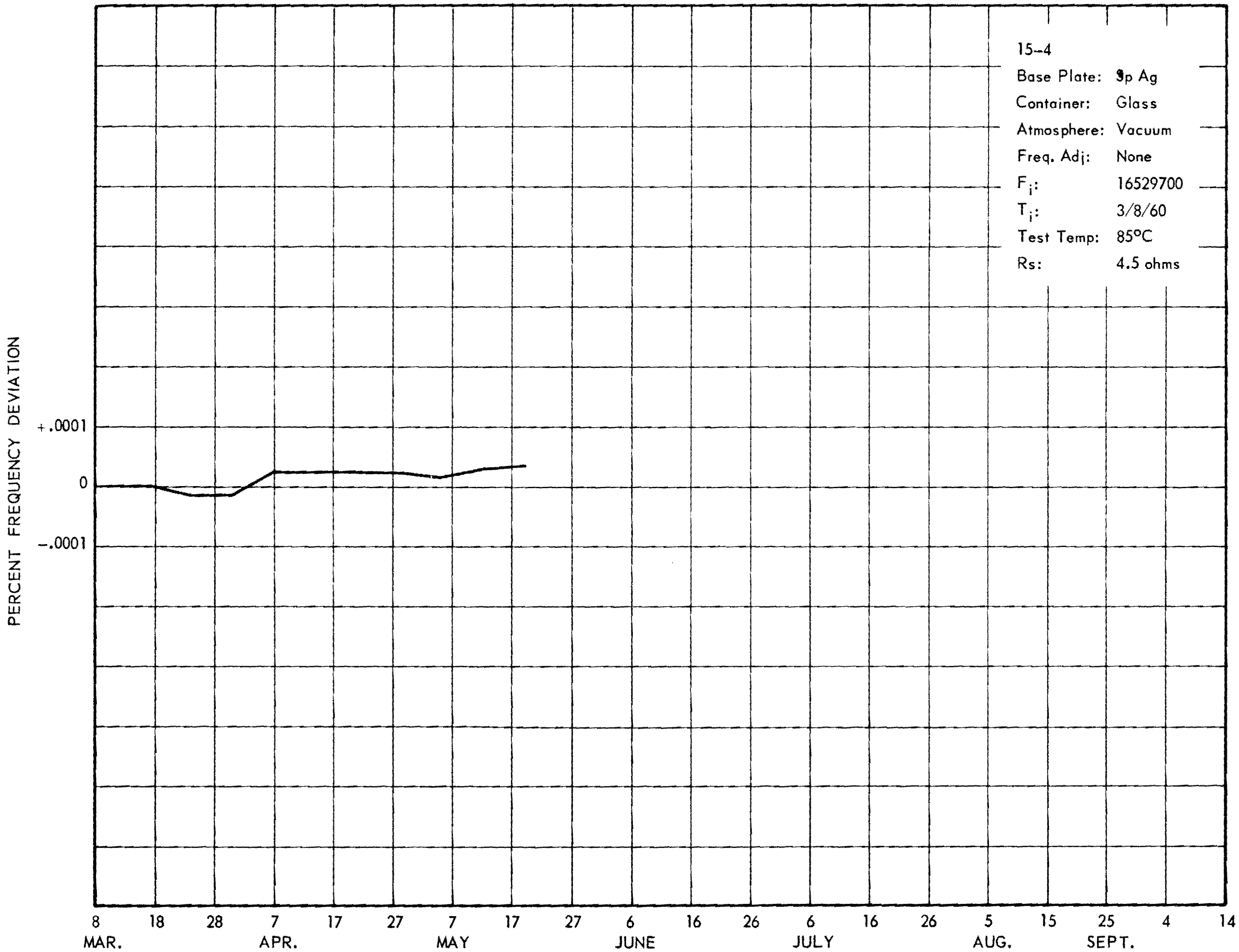

Figure 124. Plot of Frequency Data for Resonator 15-4, Sp. Ag Only, in Glass Container.

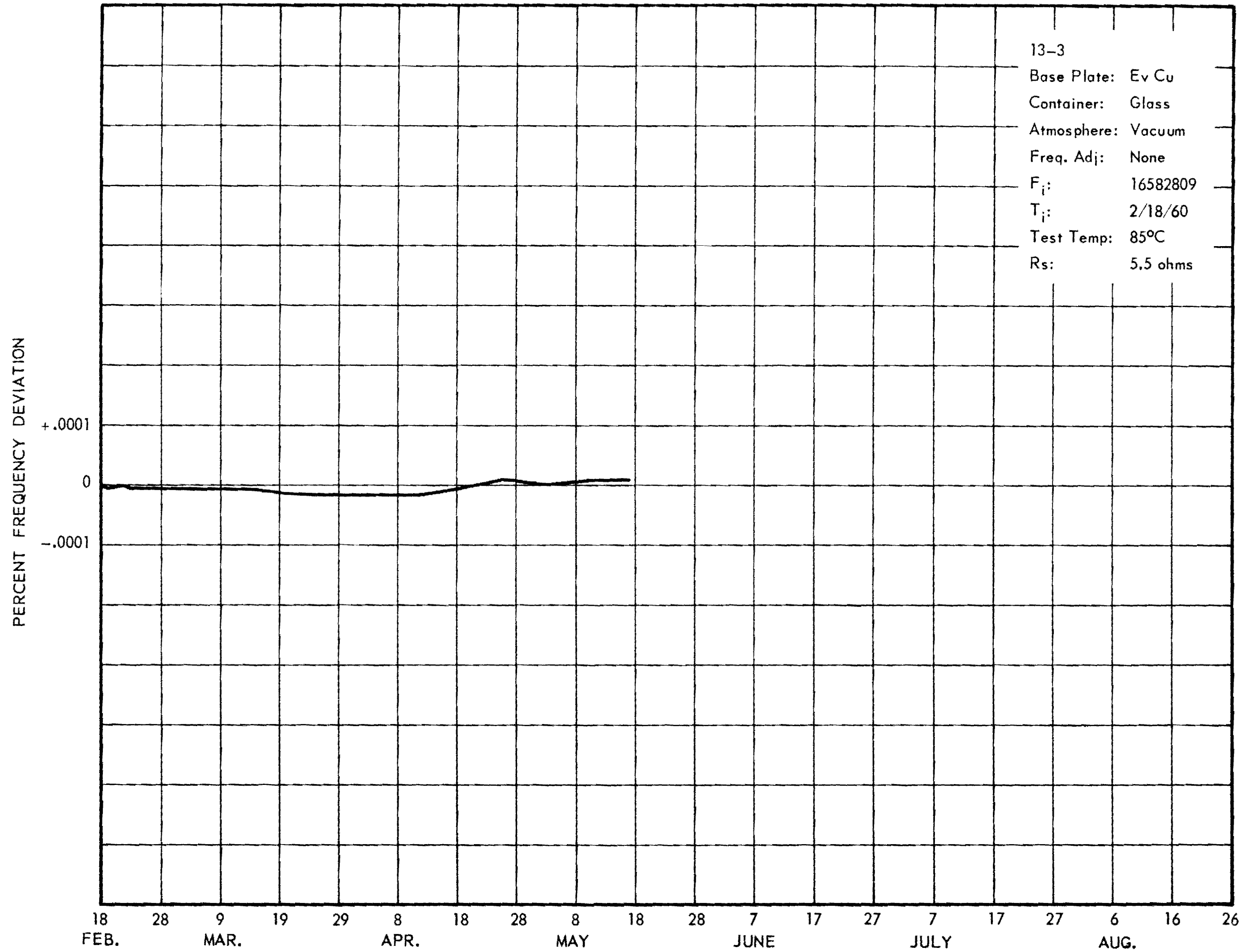

Figure 125. Plot of Frequency Data for Resonator 13-3, Cu Only in Glass Container.

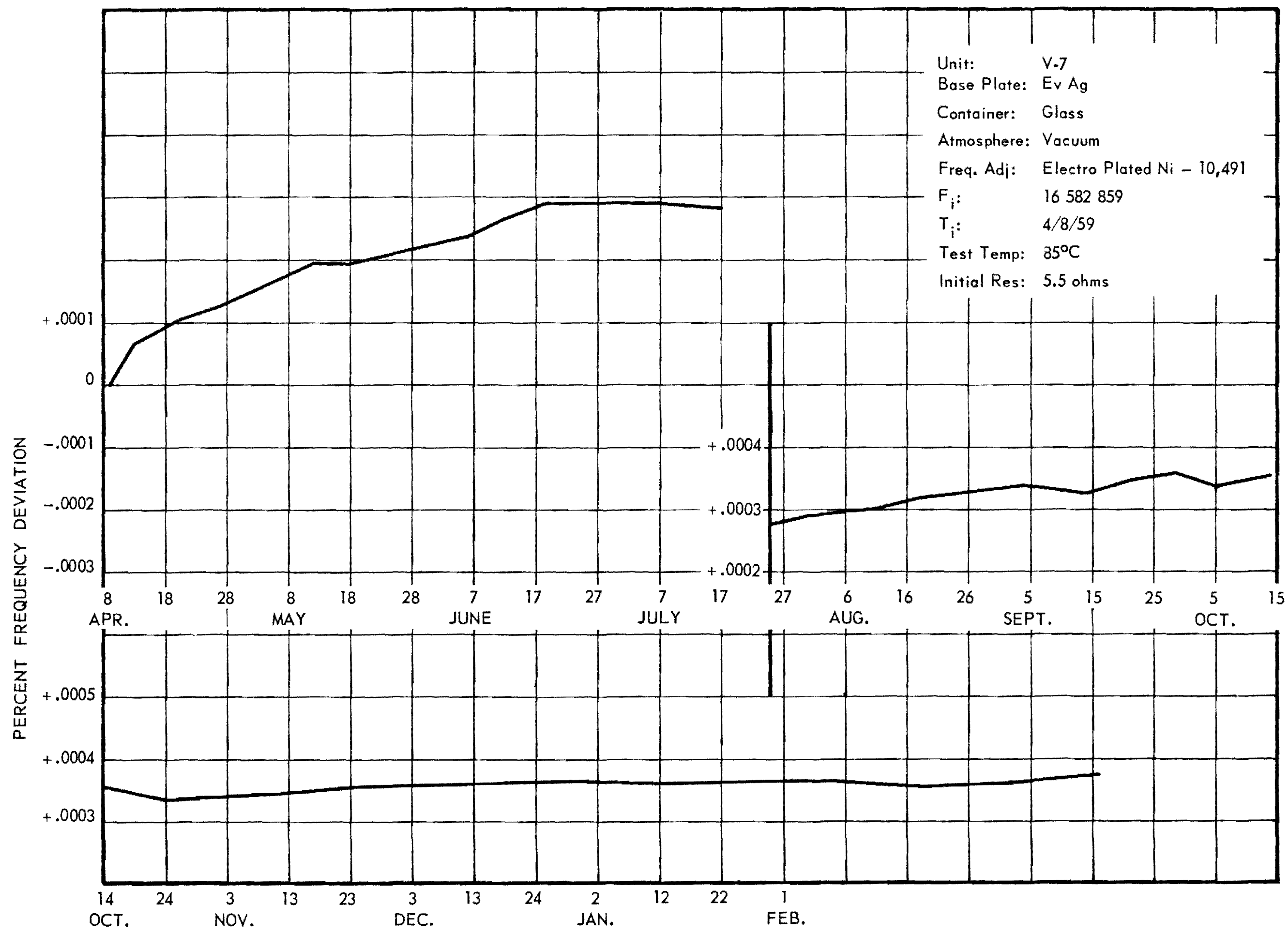

Figure 126. Plot of Frequency Data for Resonator V-7, Ag + Ni in Glass Container.

an epoxy resin.† This method of attachment eliminated exposure of the resonator to high temperatures during sealing. Although, in the first group of nine, only three proved to be stable, this was a sufficient number to show that with the proper technique good seals could be obtained in this manner.

Group 19 (six units) was mounted in the same manner and a getter material was flashed within the sealed containers; the resonators were protected from the getter by means of mica shields. These units consistently showed positive drifts over a period of 60 days with upward drifts of 3 to 5 ppm during this period. A typical pattern of behavior is shown in Figure 127.

d. Studies of 100-Mc Resonators. One group of ten 100-mc resonators was fabricated. The crystal blanks were base plated only with aluminum, mounted and sealed after the method of the T group. When operated at the fifth overtone, frequencies were approximately 100.240 mc. These units were aged at 55°C and measurements were made over a 10-day period. A plot of these measurements is shown in Figure 128.

e. Leak Tests of Industrially Fabricated Resonators. As reported last year some 600 industrially-fabricated resonators were separated into three groups consisting of an equal number from each of six industrial fabricators. The groups were stored respectively at 25°C, (room temperature) 85°C and 125°C and measurements of the change in frequency with time were made.

The measurements indicated large drifts for a predominant number of the units; the drifts were decidedly larger at the higher temperatures.

†Bondmaster No. 640.

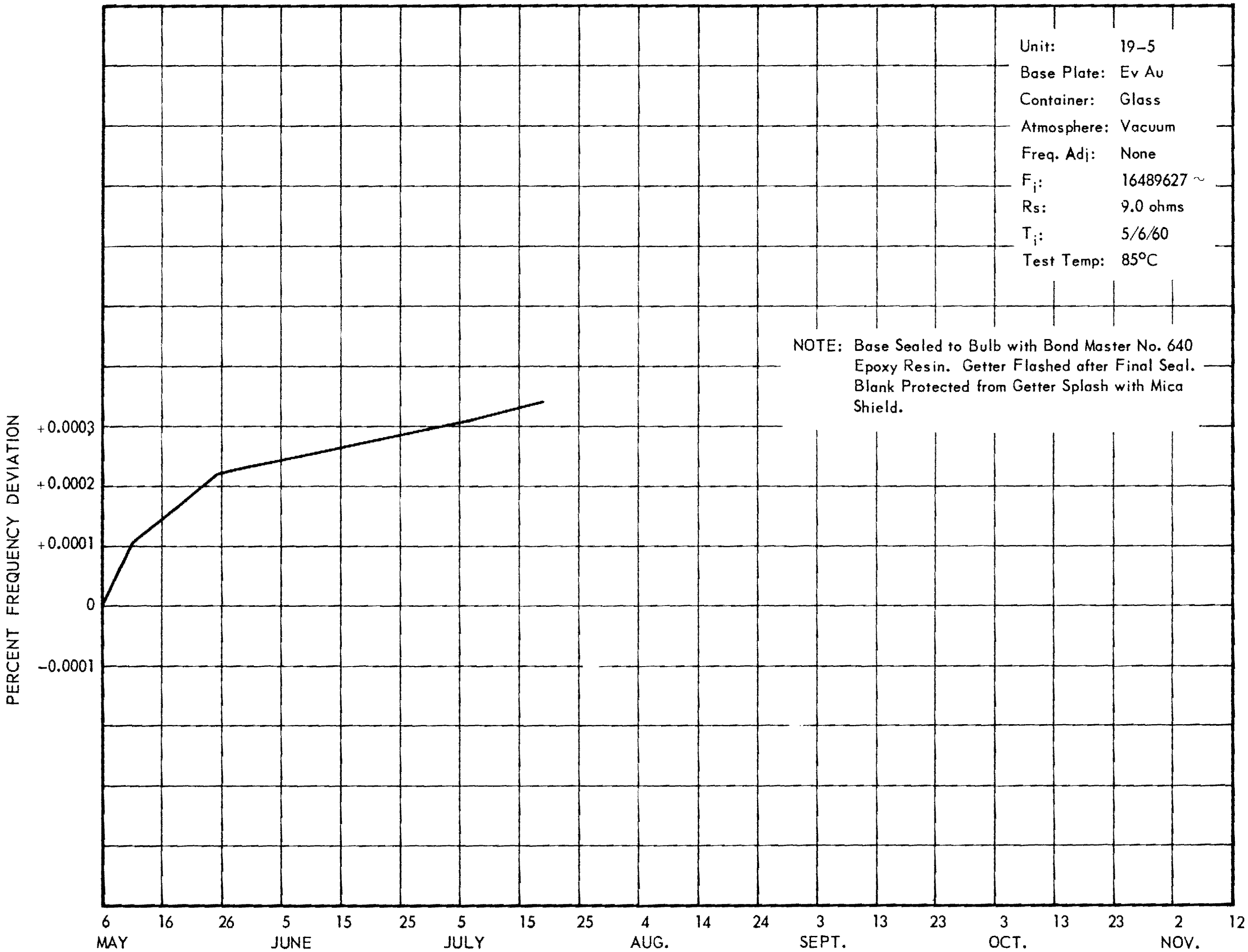

Figure 127. Plot of Frequency Data for Resonator 19-5, in Glass Container Sealed with Bondmaster No. 640 and Enclosing Getter Material.

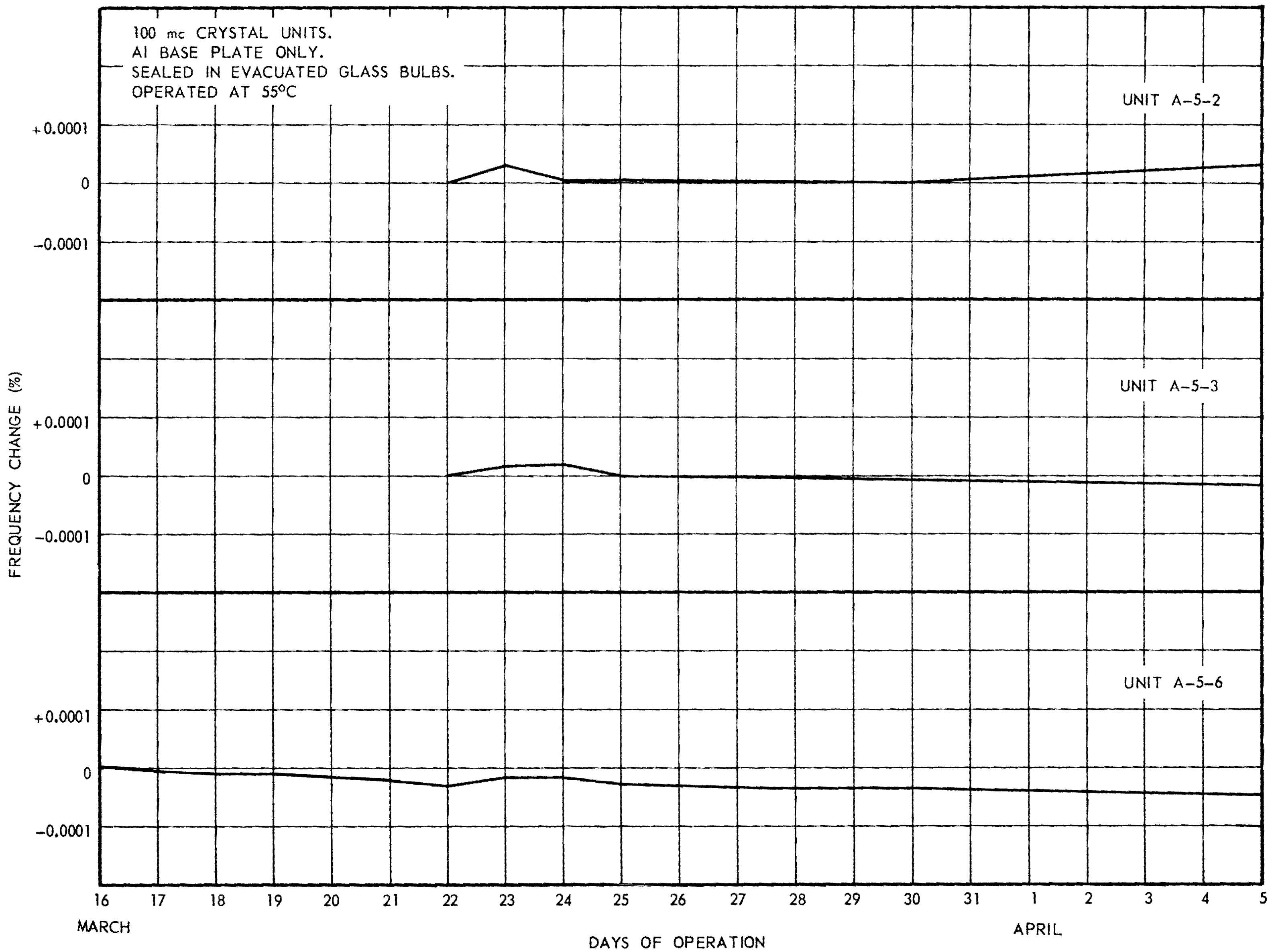

Figure 128. Plot of Frequency Data for 100 Mc Resonators, A-5-2, A-5-3, and A-5-6.

Since the leaking of the units appeared to be the only logical reason for so many poor performers, each unit was subjected to a vacuum oil leak test.

This test consists of immersion of the unit in a small container of vacuum oil such as Octoil, placing the container in a vacuum chamber and evacuating the chamber. The unit is then observed for the formation of a stream of bubbles. The observations are facilitated if the container and oil are outgassed in vacuo before the test runs. This test reveals leaks which cannot be observed in any other manner, and correlation with aging behavior as determined from frequency-versus-time plots is reasonably good. If anything, the test is hypersensitive and may indicate outgassing that does not constitute a leak. A particularly bad outgassing source is the currently-used sintered-glass ceramic base of the HC-6/U holder. The outgassing can be observed by pumping down sample bases immersed in Octoil in the manner described without attachment to cans.

A summary of the results of leak measurements on 569 of the industrially-fabricated resonators is given in Table XIII.

It will be noted that the total number of resonators indicated as leaking by the vacuum oil leak test was 472, i.e., 83 percent; approximately 14 percent had large leaks.

The resonators stored at 125°C exhibited a higher percentage of leakers than the average, especially a higher ratio of units with large leaks to those with small leaks.

The correlation between the frequency behavior of the resonators and the leak size indicated was fair. The resonators with large leaks or several small leaks usually had relatively rapid drift rates, whereas those with very small or no leaks indicated usually gave lower drift rates. A part

TABLE XIII

NUMBER OF LEAKERS FOUND IN INDUSTRIALLY FABRICATED RESONATORS BY THE VACUUM OIL LEAK TEST

Group No.	Number Tested	Number of Leakers Small	Number of Leakers Large	Number of Leakers Total	Number of Nonleakers
Resonators Stored at Room Temperature, 25°C					
1	42	39	2	41	1
2	42	24	3	27	15
3	41	27	5	32	9
4	39	20	6	26	13
5	42	27	7	34	8
6	24	21	0	21	3
Total	230	158	23	181	49
Percentage of total	100	68.5	10	78.5	21.5
Resonators Stored at 85°C					
1	33	29	0	29	4
2	33	29	2	31	2
3	33	26	2	28	5
4	33	19	5	24	9
5	32	20	6	26	6
6	32	27	4	31	1
Total	196	150	19	169	27
Percentage of total	100	76.5	9.7	86.2	13.8
Resonators Stored at 125°C					
1	24	16	3	19	5
2	24	20	0	20	4
3	24	8	11	19	5
4	23	9	10	19	4
5	24	13	9	22	2
6	24	21	2	23	1
Total	143	87	35	122	21
Percentage of total	100	60.5	24.5	85.3	14.7

(Continued)

TABLE XIII (Continued)

NUMBER OF LEAKERS FOUND IN INDUSTRIALLY FABRICATED RESONATORS BY THE VACUUM OIL LEAK TEST

Group No.	Number Tested	Number of Leakers Small	Large	Total	Number of Nonleakers
		GRAND TOTALS			
25°	230	158	23	181	49
85°	196	150	19	169	27
125°	143	87	35	122	21
Total	569	395	77	472	97
Percentages of Total	100	69.5	13.6	83	17

of the larger drift rates of resonators observed with increased temperature may be due to accelerated corrosion of a bimetallic electrode of nickel and silver in the presence of water vapor. It is apparent that the vacuum oil leak test did indicate some small leaks which did not exist prior to the test and that certain other aging parameters existed that could partially mask aging effects due to leaking. These evidences of small leaks, however, are conjectured to give evidence of probable susceptibility to leaking or to internal outgassing. Leak determination by helium leak-detector methods gave even poorer correlation with resonator aging, since many units indicated as nonleakers were shown to be obvious leakers by the vacuum oil leak test. Hence the vacuum oil leak test is a more sensitive test than the helium leak test or any other leak test currently being used in the industry. This test also indicates the location of the leak. It may indicate a very small leak, however which does not exist.

Occasional intermittent leaks have been observed and some can-coating agents may give temporary seals until exposed to a pressure reduction on the exterior of the can. It appears that sealing of micro-pores in the can may be accomplished with a suitable plastic or liquid sealant. The completed resonator would be immersed in the material in liquid condition, pumped to a pressure of a fraction of a millimeter of mercury and gas readmitted to the chamber; the resonator would then be removed from the liquid and allowed to dry. This treatment should seal many of the fine pores now causing trouble. A better base design, as previously pointed out, would also diminish the number of probable leakers.

f. Glass Versus Metal Containers. The measurements reported, with the exception of the industrially-fabricated resonators, were made on resonators mounted predominantly in glass containers. Metal containers have been suspect since an experience in 1958-1959 in which a high percentage of resonators fabricated here in metal cans were found to be leakers and from further observation of the 600 industrially-fabricated resonators just discussed.

With proper sealing, gold units performed with high stability in the metal container as shown in Figures 129 and 130 but this degree of stability has not yet been consistently achieved for aluminum-plated resonators in the metal container as noted in Figure 115. On the other hand, better cleaning of the container and improved vacuum bakeout practice may bring stabilities for aluminum-plated resonators to that of unit 17-17 in Figure 116.

The all-glass or ceramic HC-6/U base appears to be a prime suspect for leaks; the beaded-pin, compressional-seal type appears to be markedly

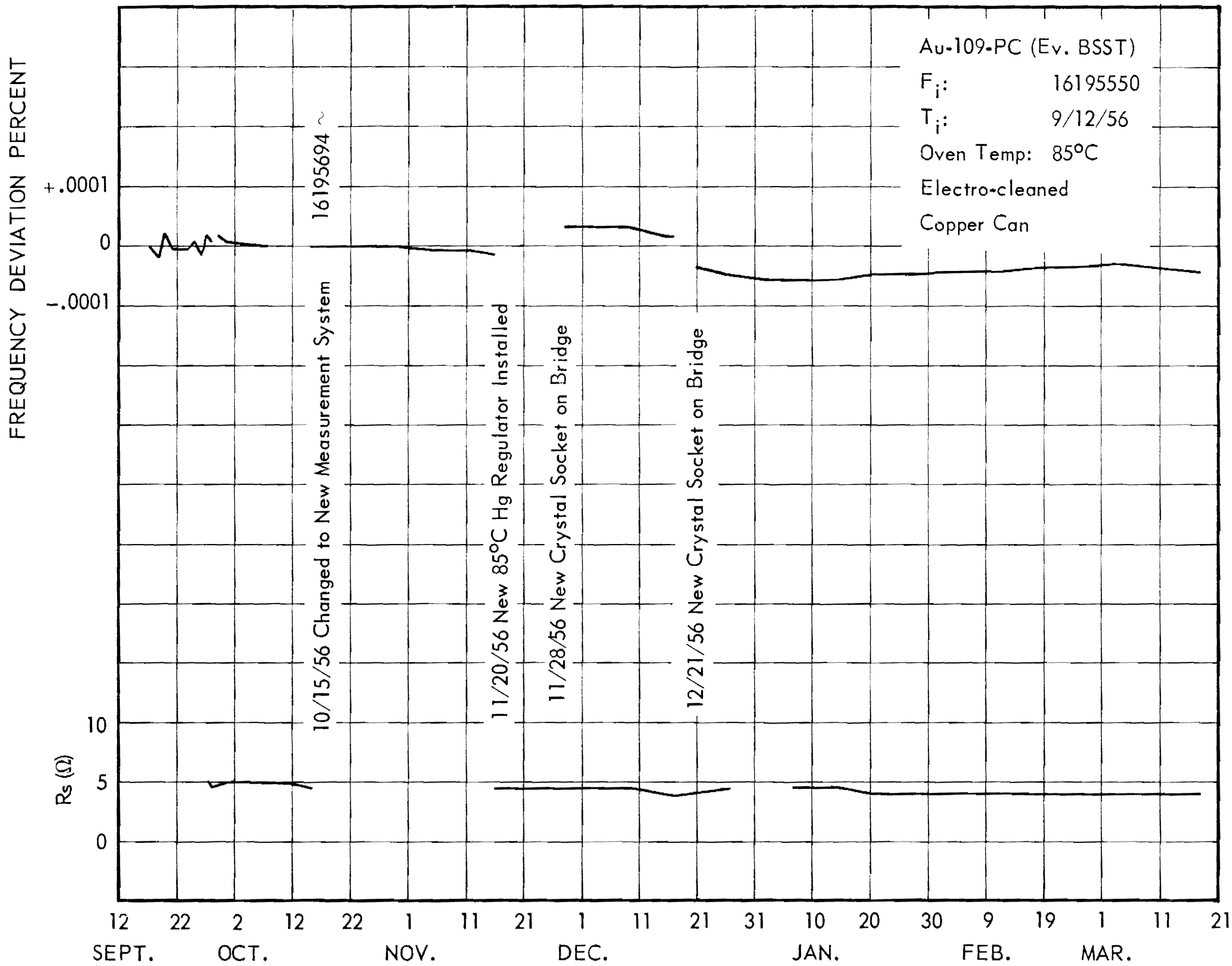

Figure 129. Plot of Frequency Data for Resonator Au 109, Ev. Au Only, HC-6/U Copper Can.

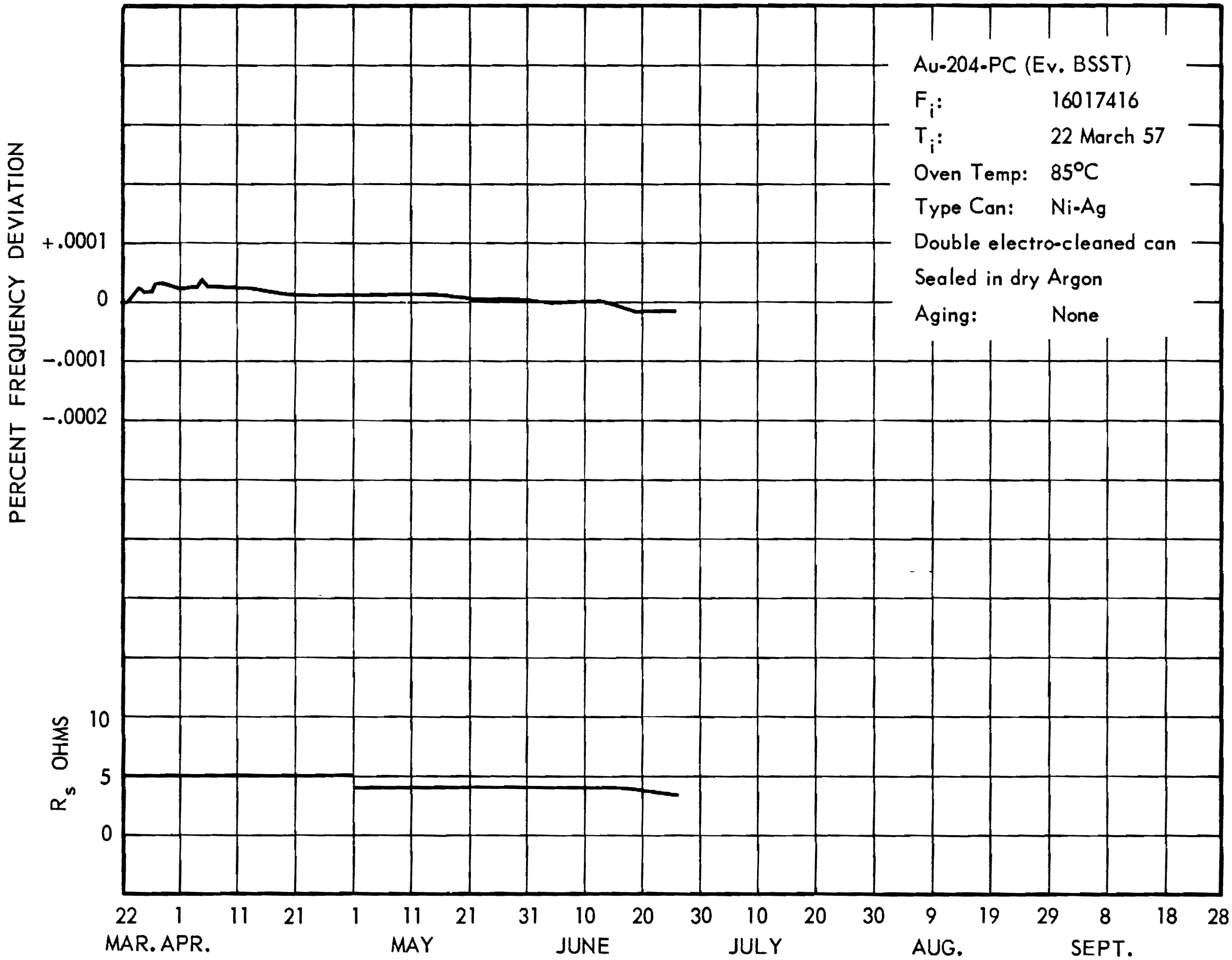

Figure 130. Plot of Frequency Data for Resonator Au 204, Ev. Au Only, HC-6/U Nickel-Silver Can.

superior to it. This is a logical observation when one compares the total area of the glass and the total length of the metal-to-glass seal interface of the two types of bases. There is a higher likelihood of failure as the length of the seal increases; and for the two designs the ratio of the one length to the other is more than 20 to 1. The sintered glass is also a source of outgassing. The rigid glass base has an intrinsic weakness in that the pins generate cracks when slight stresses are applied to them. The act of inserting or removing the units from tight sockets may create such stresses. The beaded pin type is much sturdier. Undercut pins may also be advantageous.

Proper containers and sealing techniques, however, do give satisfactorily sealed units in metal containers.

V. CONCLUSIONS AND RECOMMENDATIONS

Under Phase I, the measurement and analysis of the circular crystal were advanced as far as practicable at this time. The measurements will be more fully utilized after further analysis of the simpler rectangular crystal has provided a theoretical basis as a starting point.

The development of equipment and technique for the investigation of the charge distribution of a crystal excited by a partial upper electrode opens the way for an interesting series of experiments as a basis for theoretical advances. Although neither personnel nor funds are available now at Georgia Tech, further work in this area should be done.

The work completed on the measurement and analysis of the modes of vibration in the vicinity of the third overtone indicates the greater complexity of the modes in this region relative to frequencies near the fundamental. A most interesting area on the mode chart where a flexure mode crosses the third overtone was not reached during this investigation. This work is being continued under a non-military sponsor. Both the third overtone and the fundamental regions will be recorded as the crystal is reduced in steps of a few microns.

Under Phase II, a substitution crystal measurement system was developed and calibrated. The system satisfies the contractual requirements stated in the PURPOSE except that power dissipation can be determined only after the resistance measurement has been made. The system can furnish all of the information required for production testing of quartz crystals or for the design of crystal-controlled oscillators. The system can be further improved and transformed into a practical crystal test set by combining most or all of the individual commerical instruments into a single package.

Since the oscillator study program was initiated only 6 months before the end of the current contract it is far from completed. A number of useful oscillator circuits, both vacuum-tube and transistor, have, however, been developed. Typical short-term instabilities are, for the vacuum-tube oscillators, ±10 cycles per second and, for the transistor oscillators, ±1 cycle per second. Other characteristics of the oscillators have been determined only to a limited extent due to inadequate instrumentation. The problems of instrumentation have, however, been under careful study.

The most urgent present need in the overall frequency control problem at VHF and UHF appears to be a concentrated study of oscillator circuitry. For this study, special instrumentation must be developed for the measurement of long- and short-term stabilities under various prescribed conditions of temperature, voltage, and other controlling factors. Such factors as power output, harmonic content, and amplitude stability must also be studied.

Under Phase III, aluminum-plated resonators of 16.5-mc fundamental frequency can be fabricated to have drifts less than one part per million per year when stored at 85°C. Although overcoating may degrade stabilities slightly, aluminum, gold, silver, and copper were found to perform satisfactorily as overcoating materials in the measurements conducted. If metals other than aluminum are used as the overcoating for aluminum films, a diffusion barrier of aluminum oxide must be formed on the aluminum base plate by admitting air to the chamber before the second plating operation is undertaken.

The primary requirements for units of consistently high stability are cleanliness in all fabrication steps, an inert atmosphere, and proper hermetic sealing of the completed resonator. When these requirements have been met, films of gold, silver, copper, or aluminum may be used as the plating material and resonators of nearly uniform high stability will result. Furthermore, units in metal containers should perform nearly as well as those in glass.

The currently used HC-6/U base of glass or ceramic is a poor design and should be changed. In addition to an intrinsic tendency to fracture about the pins or rim, it constitutes a source of outgassing of various vapors in accordance with the constitution and history of the specific base.

VI. IDENTIFICATION OF KEY TECHNICAL PERSONNEL

Technical guidance for the investigation of the modes of vibration of Phase I under this contract was provided by Dr. Issac Koga, Dean of Engineering, Tokyo University. Dr. Koga received the Doctor of Engineering degree from Tokyo Imperial University in 1930. He has spent most of his professional career in the field of quartz crystal studies and applications and is noted for numerous publications. He is one of the international authorities in his field and has received many honors. Dr. Koga spent 6 weeks in residence at Georgia Tech in 1959 while the project under Contract No. DA-36-039 SC-78910 was being activated. In 1960 he was at Georgia Tech for 6 weeks, but only 1-1/2 weeks were spent on this project.

From the initiation of this contract through June 1959, Phase I of the project was coordinated by Dr. J. E. Rhodes, Jr. Dr. Rhodes devoted approximately one-quarter time to the mathematical study of the vibration of quartz. Dr. Rhodes received the Ph.D. degree in Physics at Johns Hopkins University in 1947. He has been at Georgia Tech since then as Associate Professor of Physics and Senior Research Physicist.

The experimental program was conducted by Dr. Hitohiro Fukuyo, Assistant Professor at Tokyo Institute of Technology, until his return to Japan in August 1959. Dr. Fukuyo received the Doctor of Engineering degree at the University of Tokyo in 1954 as a protege of Dr. Koga. The research equipment developed for quartz studies in Tokyo by Dr. Fukuyo was brought to Georgia Tech for the studies of circular crystals. Dr. Fukuyo was at Georgia Tech as a Research Engineer for a total of one year full-time on this and the preceding contract.

From June 1959 through June 1960, the local research activities and report preparation for Phase I were under the direction of Samuel N. Witt, Jr. as Assistant Project Director. Dr. Koga retained the responsibilities of overall guidance. Mr. Witt received his M.S. in Electrical Engineering from the Georgia Institute of Technology in 1953. He has completed his course work and the experimental investigations of his thesis for the Ph.D. He has been associated with the Engineering Experiment Station on various projects since 1951.

From July 1959 through June 1960, the major portion of the experimental program under Phase I was conducted by Mr. Yasuo Tsuzuki. Mr. Tsuzuki received his B.S. in Electrical Engineering from the Yokahama National University in 1955 and his M.S. in Electrical Engineering from the Tokyo Institute of Technology in 1957 under Dr. Koga. Mr. Tsuzuki was employed by Georgia Tech for a period of one year as Assistant Research Engineer and will depart in August 1960 to resume his teaching duties at the Yokahama National University.

The personal services on Phase I for the contract period 1 March 1959 through 30 June 1960 follow:

Name	Title	Hours
I. Koga	Project Director, Phase I Special Research Engineer	300
J. E. Rhodes, Jr.	Senior Research Physicist	285
S. N. Witt, Jr.	Assistant Project Director from July 1959 Research Engineer	240
H. Fukuyo	Research Engineer	944
Y. Tsuzuki	Assistant Research Engineer	1807

Phase II of the project was under the direction of Samuel N. Witt, Jr. Mr. Witt was employed one-half time by the project except for his period of full-time work from July 1959 through September 1959. Mr. Witt's qualifications were described in connection with Phase I above.

Mr. Vance K. Woodcox was employed full-time on Phase II of the project from March 1959 through 17 June 1960 at which time he terminated his employment with Georgia Tech. He received his B.S. in 1957 and his M.S. degree in 1960, both in Electrical Engineering, from the Georgia Institute of Technology. He had been employed at the Engineering Experiment Station since September 1957 on USASRDL contracts.

Mr. Hugh W. Denny joined the staff on Phase II of the project on 20 June 1960. Mr. Denny received his B.S. in Electrical Engineering in 1960 from the Tennessee Polytechnic Institute. He was graduated with the third highest four-year grade average in the School of Engineering.

The personal services on Phase II for the contract period 1 March 1959 through 30 June 1960 follow:

Name	Title	Hours
S. N. Witt, Jr.	Project Director, Phase II Research Engineer	1530
V. K. Woodcox	Research Assistant	2508
H. W. Denny	Research Assistant	72

Phase III of the project was under the direction of R. B. Belser. Mr. Belser received his M.S. degree in Physics from Emory University in 1949. He has had 25 years experience in teaching and research. Since 1950, his time has been devoted predominantly to research in the aging of quartz resonators under projects supported by USASRDL and in studies of thin metal films.

Mr. Belser is the author of over 60 technical reports, 30 papers, and two patents have been issued to him.

Mr. Walter H. Hicklin is a graduate of the Technical Institute of Valparaiso, Indiana, and of electronic courses given by the U. S. Air Force in World War II. He has 18 years experience in electronic circuitry, and research on quartz resonators, other electronic components, and thin metal films. Mr. Hicklin has been chief assistant to Mr. Belser for 7 years and has co-authored numerous reports and a number of papers.

Mr. J. J. Erasmus was born in the Netherlands where he received a technical school education. There he was employed by the N. V. Philips Corporation of Eindhoven as a laboratory assistant in 1946 and later as a plant manager in the production of quartz crystals. In 1956 he came to Pan Electronics of Griffin, Georgia, where he worked as a production engineer on quartz crystals until he came to the Georgia Institute of Technology on July 1, 1959. He terminated his employment at Georgia Tech on December 31, 1959.

Mr. Conrad Meaders received his B.S. degree in Physics from Emory University in 1950. His early experience was with Southern Bell Telephone Company and subsequently with the U. S. Weather Bureau. He has worked with Mr. Belser's group on thin metal films for 3 years. He has been active in the fabrication and measurement of quartz resonators and thin film resistors.

Miss Dorothy Brine is a graduate in mathematics and physics from Trinity College, Washington, with postgraduate work in philosophy at the University of Toronto. She has worked with thin metal films at Georgia Tech for approximately 4 years and has conducted studies on interferometric measurements of film thicknesses and other studies on the vapor deposition of metals.

Mr. James O. Darnell attended Berea College in Kentucky for 3 years, specializing in Chemistry. During his career at Berea, he was instructor in Wood Shop and in related activities. He has also gained a familiarity with electronics. He has been associated with Georgia Tech for 4 years and has worked with thin metal films and their uses in the fabrication of electronic components.

Mr. Mercer D. Carithers is a graduate of Air Force Schools in electronics, is skilled in the field of electronic circuitry; and has continued his studies at the Georgia Institute of Technology where he completed his B.S. degree in Physics in June 1960. He has worked full or part time for a period of 5 years on the studies of quartz crystal resonators and thin metal films and is highly skilled in quartz resonator fabrication and frequency measurement.

Mr. W. D. Dawson is a Junior in the school of Electrical Engineering at the Georgia Institute of Technology. Previous to his attendance here he had graduated from the U. S. Air Force Radar school and has had approximately 8 years of electronic circuitry experience in the Air Force and in industry.

The personal services on Phase III for the contract period 1 March 1959 through 30 June 1960 follow:

Name	Title	Hours
R. B. Belser	Project Director, Phase III Research Associate Professor	395
W. H. Hicklin	Assistant Research Engineer	2216
J. J. Erasmus	Assistant Research Engineer	344
J. C. Meaders	Research Assistant	1463

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Name	Title	Hours
D. A. Brine	Research Assistant	49
J. O. Darnell	Research Assistant	165
M. D. Carithers	Technician	302
W. D. Dawson	Technician	559

Respectfully submitted:

Samuel N. Witt, Jr.
Assistant Project Director
for Issac Koga, Project
Director, Phase I

Samuel N. Witt, Jr.
Project Director, Phase II

Richard B. Belser
Project Director, Phase III

Approved:

Arthur L. Bennett, Chief
Physical Sciences Division

Approved:

for J. E. Boyd
Director

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